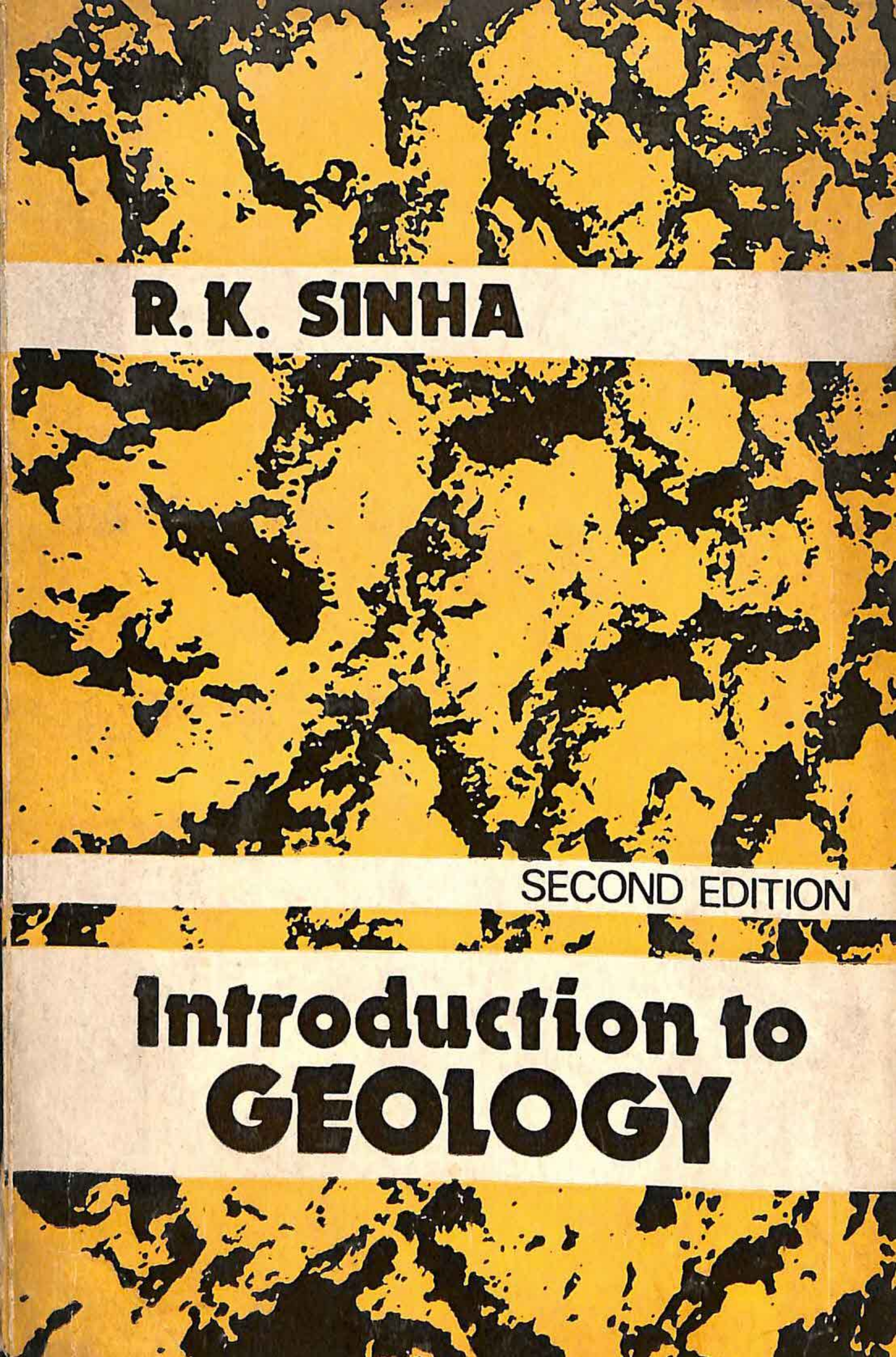

R. K. SINHA

SECOND EDITION

Introduction to GEOLOGY

AN INTRODUCTION TO GEOLOGY

SECOND EDITION

R.K. SINHA

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Preface to the Second Edition

When this book was first released in 1975, there were many suggestions to recast the entire book and make the individual chapters into specific topics say physical geology, mineralogy, petrology, structural geology, palaeontology, stratigraphy, etc. so that it could be used straightway as a textbook for preliminary students. I value the suggestion very much. At the same time, I must express my limitations as I am not a teacher myself. It would be unfair on my part to recast the topics for the preliminary students from the several excellent texts available on the subjects. The job is best left to the teachers.

As indicated in the preface to the first edition, the book is intended to arouse interest in understanding and learning geology—the science of the earth's crust on which we live. It tries to provide a leavening effect in the minds of students for grasping and appreciating the subject in the right perspective. It thus describes mainly the interpretative parts of the various subjects taught in the discipline of geology. This book is meant to be an aid, rather I should say, for constant reading by students and teachers alike.

I am of the view that the various subjects which are being taught today under the realm of geology should be covered within the undergraduate course, i.e. up to the B.Sc. level. It is possible to do so by introducing it as an optional or compulsory subject at the junior level. In the post-graduate level effort should be made to impart specialised teaching with a view to reorient the students thoroughly on the practical aspects of the geological science. It is suggested that in the postgraduate course subjects like structural and field geology mineral exploration, geochemistry, economic geology (ore genesis), petrology including ore microscopy and instrumentation, petroleum and coal geology, hydrogeology, photogeology, mineral economics, ore processing, palaeontology, environmental geology, geostatistics and application of computers, etc. should be introduced and taught. Different universities may choose to impart training in a selected few specialised aspects. Unless we take recourse to reorienting the methods of teaching, we would remain far behind in making the students useable immediately after their education is complete. It is my earnest desire that the concerned institutions, boards of studies and teachers may constantly remain vigilant to the changing pattern of requirements and accordingly modify the teaching methods and subjects.

R.K. SINHA

Preface to the First Edition

The teaching of geology is, at present, confined exclusively to universities. It is not taught in Indian schools. It is my firm conviction that geology—the basic science of the earth's crust on which we live—should be introduced as an optional subject at the higher secondary level so that the elements of geology could be taught in the school itself.

This book is intended to be a beginner's course in geology and mining. It describes the interpretative part of the various subjects taught in the discipline of geology and explains many of the logical questions which arise in the course of regular studies. There are a large number of excellent textbooks on different branches of geology but a work with the treatment as in the present book is perhaps non-existent.

The topics covered in this book have been selected keeping in view the requirements of the students. The events beginning from the origin of the earth to making and shaping its crust in the present form, processes involved resulting in various mineral deposits, and the geological criteria adopted in searching for them have been detailed in a simple and coherent manner making them easily intelligible to beginners. It is my earnest hope that the book would appeal to students of geology and allied disciplines and would help them in understanding and appreciating the subject in the right perspective in their advanced studies. It would also prove handy to teachers and professionals.

I was greatly inspired in preparing this book by my sons, Amitabh and Anurag. Without their inspiration this book would have not been possible.

In writing this book, I received invaluable help from my colleagues and friends. To all of them, I am most grateful. I am indebted to M Narsimhan, H Anantha Ramiah, and C M Doshi for their constructive criticism and suggestions. I am especially thankful to P M Rao and Mrs Vasudha Deshmukh for ungrudgingly taking the trouble of editing the manuscript. To Gurdev

Singh and M R Sen Gupta, I wish to place on record my sincere appreciation for preparing the illustrations. Last, but not the least, I must thank S V Nimje and V V Telang for speedy secretarial assistance.

R.K. SINHA

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1

What is Geology—An Introduction

Geology is the science of earth's crust and its environment. The crust forms the outer layer of the earth. This science enables a thorough understanding of the crust, the manner it is laid, of what it is composed, how the minerals and rocks are deposited underground and on the surface, and how hills and mountains originate. Geology tries to explain these fascinating phenomena of nature. Unravelling its history is quite exciting. The crust presents an intricate picture—the outcome of years of labour of natural processes. These processes, the geological phenomena, some acting from within and some on the surface, have all contributed in shaping the crust in their own way, giving rise to a variety of minerals and rocks that are known to us today. The crust is the source of all minerals, *viz.*, coal, petroleum, sulphur, copper ore, iron ore etc., providing an invaluable asset to mankind. The mystery of ore forming fluids, involving their sources, their physical character, their methods of transport and their manner of deposition has always been the subject matter of scientific investigation to the geologist. What we actually try to learn in geology is to understand the mechanism of various natural processes involved in making and shaping the earth's crust, more so about the processes involved in the formation of mineral deposits.

The crust measuring some 50 km in thickness is sub-divided into two parts, the lower portion known as 'sima' and the upper portion as 'sial'. Such sub-division is based on the information furnished by the seismic waves. The sialic portion measures about 16 km in thickness. The beautiful mountains, valleys, plains, oceans, lakes, rivers and glaciers seen around us were born as a result of several crustal movements, glaciation, igneous, sedimentary and metamorphic activities coupled with repeated cycles of uplift, faults and folds, weathering, erosion, deposition and similar other geological processes. These activities changed the face of the earth time and again. These have also been responsible in giving rise to mineral deposits. Sun, rain, frost, glaciers and rivers are the chief weathering and eroding agents. These are first class landscapers as well. Such phenomena are going on ever since the earth solidified some 4,000 million years ago. The "Continental drift theory" or the "Platetectonic theory" about which we shall read later in Chapter 6 provides us an understanding of far-reaching significance about the depth to which a mineral deposit can occur. It proves beyond doubt that the present configuration of the land and sea is an outcome of an important geological phenomenon of gradual rifting and drifting of sialic layers lying over simatic mass. The land mass now forming the continents, it appears, has slid along the weaker zones of sialic layers as if each layer is placed one upon another like a plate. More than 120 layers have been recognised in sialic portion. It is evident that the weaker zones which may be regarded as in a plastic or semiplastic state giving way to sliding of continents will not be congenial for ore forming fluids to crystallise. In other words, it provides a positive indication that there are no encouraging chances of encountering mineral deposits below the maximum depth of the oceanic floor. The deepest depth of oceanic floor is found off the island of Marianas, Philippines in the Pacific Ocean. The depth of this trench is 10.55 km from the surface. It may thus be inferred that the possibility of finding mineral deposits is limited mostly to the upper half of the sialic portion. The maximum depth to which a mine has been worked is a little over 3 km as in the case of Kolar gold mines, Karnataka. In the case of petroleum, the deepest well ever drilled is about 8 km in Pecos county, Texas, USA. The recent finds of manganese nodules littered on the oceanic floors at a depth of 4-5 km from the surface of the sea in the Pacific, Atlantic and Indian oceans with a high incidence of nickel, copper and cobalt are the results of volcanic activities on the oceanic floors. Such volcanic activities were largely associated with the continental drifts.

Minerals of which utility have been established are found to occur in some places as local concentrations of varying sizes in the form of veins, lenses, pockets, impregnations in rocks and as a sheet of beds. They were formed in different geological periods under various geological settings and environments. How minerals are formed, how they occur, their genetic relations to specific rock types and methods of searching for them are some of the problems requiring special understanding in the realm of geology. The application of geology in a practice is confined to the sialic portion mainly down to a few kilometre depth. Even so, the structure of the upper part of the crust is so complex that it has not been possible to know all about it. The geology of an area or a region varies greatly depending on the manner it was acted upon by different geological processes. Nevertheless, it has been possible to ascertain events on land from about 600 million years ago till today with a good level of approximation. The science of geology has begun probing the continental shelves and oceanic floors. The results are quite fascinating. The continental shelves which are outward extension of the land mass sloping gently and submerged under the sea are found veritable sources of many useful minerals, chiefly, the natural oil and gas. The width of continental shelf is found widely varying from country to country extending from few metres to as wide as 1,500 km. The country which has got a wider continental shelf is naturally fortunate in having many living and non-living resources.

A number of subjects are taught at the university level to the students of geology in order to impart to them a thorough knowledge in this field. Such important subjects are the physical geology—the study of nature and development of landscape; stratigraphy—the study of the sequence of rocks formed in the earth's crust since the beginning of the earth's history; petrology—the study of the composition and origin of various rocks; mineralogy—the study of physical and chemical characters including atomic structure of minerals and methods of their identification; palaeontology—the study of ancient life as revealed by the fossils found in the bedded rocks; oregenesis—the study of modes of occurrence and formation of mineral deposits; structural geology—the study of methods of interpreting the disposition of formations and their structure originated by faults and folds and such other crustal movements; and field geology—the study of method of mapping, prospecting, interpretation and recognising field criteria in search of minerals.

These subjects form the core of the geological science. Specialised aspects are taught in the fields of petroleum geology, mining geology, ground water geology, engineering geology, photogeology, geochemistry and geophysics. Teaching of marine geology has also been introduced lately. There are other subjects, *viz.*, oceanography, seismology and isotope-geology, which have branched out of geology forming separate disciplines of study. Nevertheless, these have also a direct relation with the geological studies in acquiring a thorough understanding of the earth's crust. It is not intended here to go into the details of individual subjects as it is outside the purview of this book. In the treatment of this text more emphasis has been laid in explaining the significance and describing the interpretative aspects of the subjects in order to provide preparatory background to the students in understanding "geology" in the right perspective.

2

Earth and Its Position in Space

The study of geology cannot be regarded complete unless the earth's relative position in space and time is well understood. It will be difficult to get a conceptual idea of the earth's crust without a proper understanding of its origin. It is now well established by astronomical and astrophysical studies that our earth forms one of the nine planets moving around a single star, *i.e.* the present sun. The sun forms a family, called the solar system, consisting of 9 planets, 31 satellites, millions of asteroids, meteors and numerous comets. All planets move around the sun at a tremendous speed in fixed orbits from west to east. Satellites follow the same direction around their planets with the exception of one satellite of Saturn, and the eighth, ninth and eleventh satellites of Jupiter which move from east to west. The earth has only one satellite, the moon. The solar system occupies a fraction of space at one end within our stellar system known as the Milky Way. In this galaxy, there are innumerable solar systems like the family of our sun. The millions of stars we see in the sky within the confines of our own galaxy are spheres of glowing gas, some of them several times larger than the sun. These stars are situated far away from the sphere of our solar system. Nothing in the heavenly sky is stationary. All stars move at a tremendous speed within their orbits. The nearest star neighbour has been named Proxima Centauri and it is situated about 43 trillion km (43×10^{12} km) away from the sun. The average distance between the stars is 8 to 10 light years, one light year being the distance light covers in $365\frac{1}{4}$ days travelling at a velocity of approximately 2,98,000 km per second. Such great distances are beyond our comprehension. Planets do not glow. The Milky Way is so extensive that light travelling at 2,98,000 km per second will take more than 1,00,000 years to travel across its width. Dispersed in space are crores of galaxies like the Milky Way. The nearest galaxy to the Milky Way is Andromeda which is about 1.5 million light years away. The Milky Way galaxy together with others forms the universe, the cosmos or space rightly described as limitless.

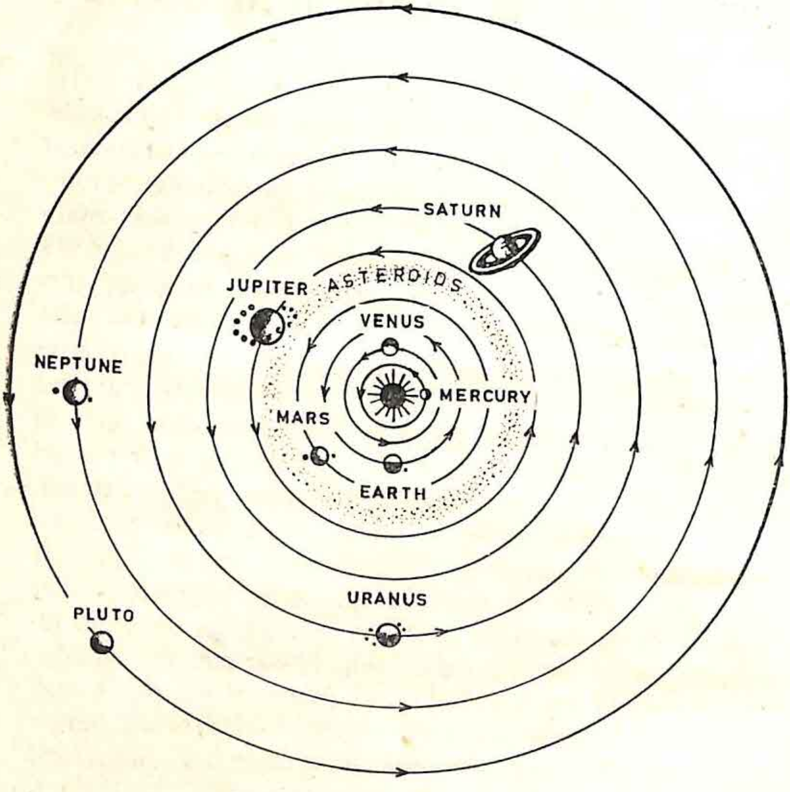

FIG. 2.1. Our solar system.

How earth was formed is nearly anybody's guess. Until now, no scientific basis has been established to show how the earth, which is a part of the solar system, came into existence. Astronomers believe that some 5,000 million years ago, two great stars from the galaxy of the Milky Way, far bigger than the size of the present sun, came close to the gravitational pull of each other and that this resulted in pulling out of several huge masses, forming the solar system. How such events took place remains yet a mystery. All the hypotheses put forth so far on the origin of the solar system, rather of the earth, are speculative. The fall of small meteor particles continuously on the earth, however, indicates that breaking of masses from one or several stars does take place. Meteorites quite big in size measuring over a km in diameter have also been reported. A very good example of a large meteorite is offered by Lonar lake of Buldhana district, Maharashtra, which was formed by the impact of a fallen meteorite.

Whatever be the manner of the earth's origin, it is clear now that our planet is an integral part of the whole cosmos. Hence there is an intimate relation in the matter of chemical composition between earth and other extra-terrestrial bodies.. This has been proved beyond doubt by the spectra of the sun and other stars. It is thus possible to know about the internal composition and structure of the earth by studying the chemical composition of these extra-terrestrial bodies available to us in the form of meteorites. In other words, it may be appropriate to say that the earth offers a fair sample of the matter composing not only the solar system but also our galaxy and perhaps even the entire universe. It is also revealing that many of the physical aspects of the earth are affected by the interaction of other planetary bodies with the earth. Since the moon is closest, its influence on the earth is the maximum. A high tide during a lunar day is one of the many examples of such an effect on the earth. Recent astronomical studies show that the earth does not move steadily in its orbit, but often gets disturbed by external forces which shake its whole body. It reverts to its original position after the effect ceases. One of the causes of deep-seated volcanism is related to this phenomenon of the earth. Many other crustal changes follow this action.

In the solar system, the earth is the densest of planets and satellites. However, in size it is smaller than many other planets. For example, Jupiter is 11 times larger in radius than Earth. Similarly, Saturn, Uranus and Neptune are also larger than Earth. The 4 inner planets, *viz.*, Mercury, Venus, Earth and Mars, are smaller but dense compared to the outer 4 *viz.*, Jupiter, Saturn, Uranus and Neptune, which are bigger in size but less dense. Little is known about the outermost planet Pluto which was discovered as late as March 1930. The inner and

TABLE 2.1. SOME BASIC DATA OF THE SOLAR SYSTEM

Object	*Distance from sun million km*	*Mean diameter in km*	*Year (Time required for one revolution around the sun)*	*Day (Time taken to complete one day)*	*Known satellites*	*Mass (Trillion tonnes)*	*Mean density gm/cc*
Mercury	57.6	4,656	88 days	88 days	None	360	5.3
Venus	107.2	12,128	225 days	Unknown	None	5,360	4.95
Earth	148.8	12,756	1 year	1 day	1	6,590	5.517
Mars	225.6	6,624	1.9 years	24.6 hours	2	705	3.95
Jupiter	772.8	138,560	11.9 years	10 hours	12	2,090,000	1.33
Saturn	1,420.8	115,680	29.7 years	10.5 hours	9	625,000	0.68
Uranus	2,848	47,200	83.7 years	10.7 hours	5	96,000	1.56
Neptune	4,480	44,480	166 years	12.7 hours	2	116,000	2.47
Pluto	5,856	5,910	247.7 years	6.4 days	Unknown	Unknown	
Sun	—	1,384,000	—	25.33 days	—	2,200,000,000	
Moon	—	3,456	—	27.3 days	—	81	

outer planets are separated by millions of asteroids (fragmented planetary bodies). These asteroids are regarded as pieces of an unknown planet once existing and which was moving in an orbit around the sun between Mars and Jupiter. The planet blew up due to tidal waves caused by its approaching either Mars or Jupiter. Of all the planets and satellites, only the earth appears to contain an atmosphere essential for the growth of life. The earth could retain the atmosphere by its force of gravity (980 cm/sec.^{2}) because of a high mass per unit volume, *i.e.* density, which has been estimated at 5.517 gm/cc.

SHAPE AND SIZE OF EARTH

The earth is spherical in shape with slight depressions at the north and south poles. The development of a spherical shape is the outcome of a natural process. Any gaseous mass or liquid mass tending to become a liquid or a solid tends to occupy the least surface area which is possible only by acquiring a spherical shape. The most recent and graphic proof of the spherical form of earth has been provided by extremely high altitude photographs taken by spacecrafts. A slight bulging at the equator and depressions at the poles have been formed due to spinning of the earth along an imaginary axis connecting the north and south poles. The diameter at the equator is approximately 12,755 km whereas between poles it is 12,711 km. In calculating the dimension of the earth, the Pole Star (known as *Dhruva Tara* in Hindi) has been found most helpful. If one travels northward from the equator towards the north pole, he will find the star rising higher and higher until he reaches the pole where the star is directly overhead. Careful measurements show that the star rises one degree in about 111.3 km. Since there are 360 degrees in a circle and each degree along a meridian is equal to a distance of 111.3 km, it follows that the earth's circumference is 360 times 111.3, or about 40,068 km. Once the circumference is known, the calculation of radius, volume, density etc. becomes very simple by using the following formulae:

$$\text{radius} = \frac{C}{2\pi}\,;\ \text{volume} = \frac{3}{4}\pi r^3;\ \text{density} = \frac{m}{V}$$

where

C=Circumference
V=Volume
m=Mass
$\pi=\frac{22}{7}$, a constant volume.

The mass of earth is calculated by an application of Newton's law of gravitation represented by formula:

$$F=G\frac{m_b m_e}{r_e^2} \qquad \ldots(1)$$

where, $G=(6.670\pm0.005)\times10^{-8}$ dynes cm^2 gm^{-2}, a gravitational constant.

m_b=mass of a body
m_e=mass of earth
r_e=radius of earth.

Now from Newton's second law of motion we have:

$$F=m_b g \qquad \ldots(2)$$

where g is acceleration due to gravity=980 cm/sec^2.

Since equations (1) and (2) are the same we have the following equation:

$$m_b g=G\frac{m_b m_e}{r_e^2}$$

$$\therefore \quad g=G\frac{m_e}{r_e^2}$$

$$\therefore \quad \text{Mass of earth } (m_e)=\frac{g r_e^2}{G}.$$

The mass of the earth has been found to be 5.98×10^{27} g; its volume 1.083×10^{27} cc; mean density 5.517 g/cc and mean radius 6,378 km.

We shall study the other details of the earth and its interior in the next chapter.

3

The Earth's Interior

On the surface, several varieties of rocks and soils are found in a continuous stretch interrupted only by vast oceans, lakes and rivers. These rocks and soils are readily available for study. Some deep-seated rocks emerging as volcanic eruptions and depositing on the surface are also available for study. Volcanic lava comes out to the surface from a depth of about 60 km or less. Other means of getting at the rocks deep down are by opening mines or making a drill hole. By and large, mines are shallow and average from surface excavations to 300 m. In the case of petroleum the depth averages about 3,000 m. In reality the material available to us for visual inspection is from a depth of a few metres at the best. But the earth's radius is 6,378 km. How then are we to study the interior? What lies beneath and how is the structure? Earthquakes and meteorites provide an answer to the possible structure and compositions inside. How surprising it is that an earthquake which is dreaded for human suffering and material loss has also some virtue in deciphering the structure. It could be possible from the study of seismic or earthquake waves and their behaviour and velocities travelling down through the earth. Nobody need wait now for an earthquake to happen for study purposes. An earthquake wave can be generated artificially by exploding high power dynamite or a bomb. Such study forms a part of seismology. Formerly, this science had a restricted field of application limited to ascertaining the foci and intensities of earthquakes and demarcating areas of earthquake zones. It is only a short while before the Second World War that seismologists tried to interpret seismic waves in understanding the internal structure of the earth. Since then seismology has made a substantial contribution to geological knowledge. Meteorites, on the other hand, help us in deducing the possible composition as well as densities of the interior. In the case of many meteorites tested so far, it has been found that they do not tally with most of the common rocks found on the surface either in chemical composition or density. Meteorites being the only source of astral bodies are regarded as representing the hidden layers of the earth. It is deduced that the rocks comparable to the composition of the meteorites must be available deep down below the surface. It may be appreciated that no body has seen the deeper horizons, as there is no means of access to them. The structure of the earth as given in Fig. 3.1 has been modelled by interpreting the facts revealed by seismic data and further corroborated by the meteorites data and geological facts.

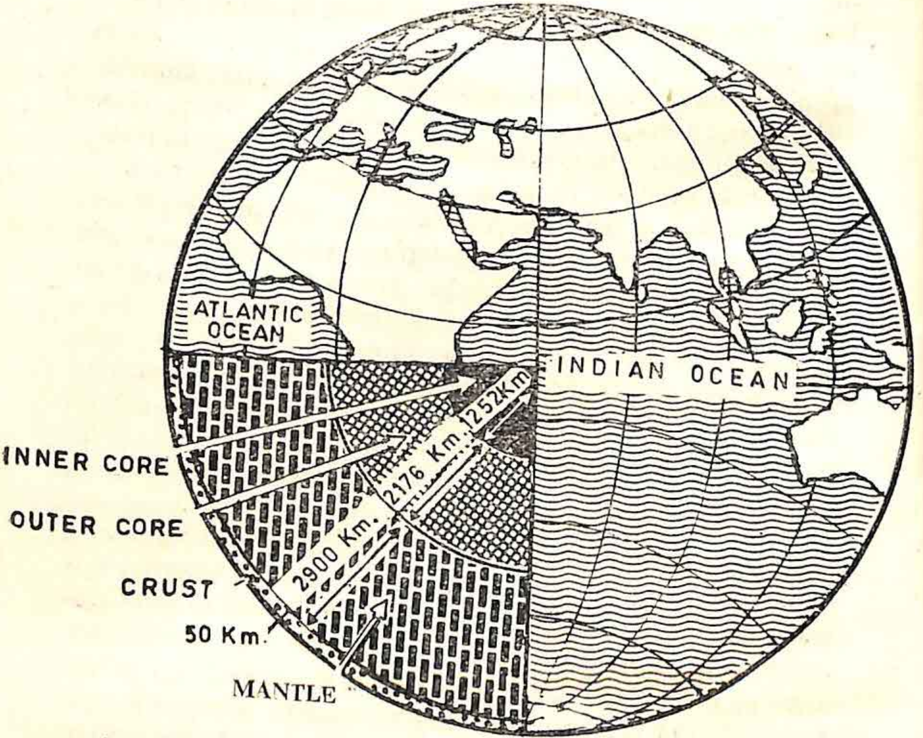

FIG. 3.1. Interior structure of the earth as revealed by seismic data.

How Seismic Waves Interpret the Structure

Earth is like an elastic body. When an earthquake takes place, it releases several types of waves, which are classified into primary (*P*), secondary (*S*) and surface (*L*) waves. These waves travel differently in different rocks. For our purpose, *P* and *S* waves are important as only they penetrate the earth. *L*-wave is found to travel only on the surface. *P*-waves travel about 1.7 times faster than the *S*-waves and even faster than *L*-waves. *P*-wave travels just like a sound wave in which each particle vibrates to and fro in the direction of propagation, causing compressional-dilatational (expansional) motion in the media. It has the property of travelling through all media—solid, liquid and gas. The mode of propagation of *S* waves can be compared with a light wave in which the motion of each particle is at right angles to the direction of propagation. The velocity of *S* waves depends exclusively on the rigidity and density of the medium. If the rigidity of a medium is zero, as in the case of a liquid or gas, *S* waves cannot travel through it. Now having understood the properties of earthquake waves, we can proceed further to understand how they explain the structure. Suppose an earthquake is created artificially at a particular place and in a fixed time. The released waves will start travelling immediately. Since *P* and *S* waves travel at different speeds, they soon appear as two phases. The separation of *P* and *S* waves becomes greater, the farther they travel. Now, suppose the time of arrival of these two phases is recorded correctly by means of seismographs placed at known interval at different places on the earth; a travel-time curve can thus be prepared by plotting the distances of the seismograph stations on the *X*-axis and time of arrival of waves on the *Y*-axis (Fig. 3.2). These standard travel-time curves shown in Fig. 3.2 have been prepared and perfected after successive investigations over the past several decades by eminent seismologists. The discovery of the earth's internal structure is based entirely on the interpretation of the travel-time curves. The work involved in it is not so simple as it appears to be. An earthquake releases several types of *P* and *S* waves which can be classified as P_1, P_2; P_1P_2. . . . and S_1,S_2; S_1S_2. . . etc. which are further complicated by reflection; refraction; diffraction; and dispersion. Thus, a very complex wave pattern is

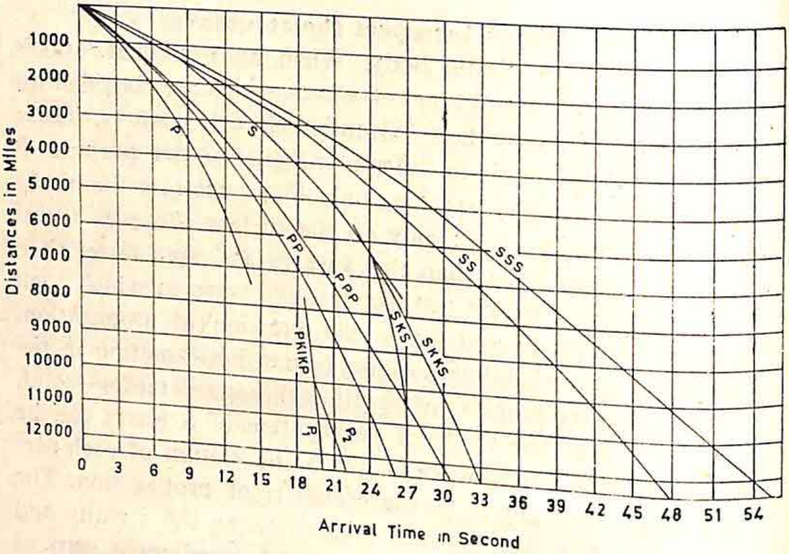

FIG. 3.2. Modern travel-time curves of seismic waves.

recorded by a seismograph station and it needs experienced seismologists to decipher it. It is beyond the scope of this book to go into the details of the techniques and we should be satisfied here in knowing the behaviour of the initial *P* and *S* waves. It is found from the seismic data that the *P*-wave which travels approximately at the rate of 6-7 km/sec. in the outer layer of the earth suddenly increases its velocity to 8 km/sec. as soon as it touches the boundary of the mantle (Fig. 3.3). Thereafter, the *P*-wave proceeds with an increasing velocity and attains the maximum of 13.64 km/sec. at 2,900 km level. The velocity of *P*-waves then suddenly falls to 8 km/sec. as if it has entered altogether a new medium. This is a most important feature of the earth's interior. It indicates clearly that the medium below 2,900 km level for a length of 3,428 km consists altogether of different substances. It has been named the core of the earth. The *P*-wave provides other valuable information of the core. As soon as it enters the core, its velocity shows some rise up to 2,176 km before becoming constant. The *S*-wave, on the other hand, is altogether deflected at 2,900 km level providing positive evidence of a liquid medium at that depth. Let us again revert to Fig. 3.2. It will be noticed that

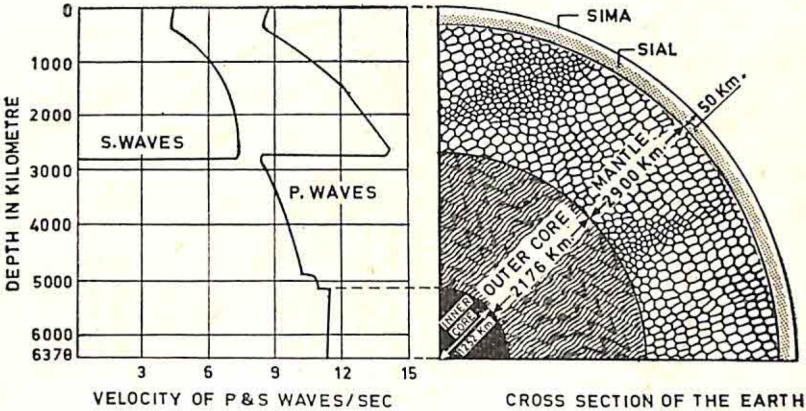

FIG. 3.3. The figure indicates the velocities of *P* and *S*-waves travelling down the earth and how they interpret the structure inside.

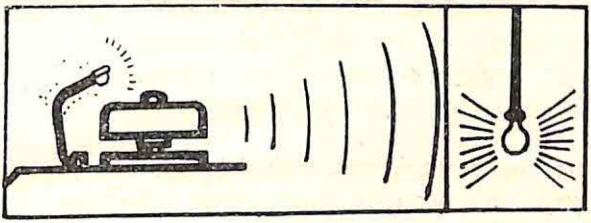

FIG. 3.3 (A). *P*-waves travel like sound (left). *S*-waves are similar to light waves (right) which travel in straight lines.

the travel-time curves for *P* stop at about 7,300 miles and that for *S* at 7,400 miles. It is for the simple reason that the reflection and diffraction of *P*-waves stop at that particular horizon, and continue to proceed further as refracted waves. *S*-wave is not recorded beyond 7,400 miles as it gets altogether deflected as soon as it reaches the boundary between the mantle and the core. In Fig. 3.4, the behaviour of *P* and *S*-waves while travelling down the earth has been illustrated. It may be observed from this figure that due to deflection of *S*-wave and refraction of *P*-wave, there occurs a shadow zone between which an earthquake tremor is not perceptible. Inge Lehmann, a Danish seismologist with the help of very sensitive seismographs discovered that *P*-waves were penetrating the shadow zones as well, although

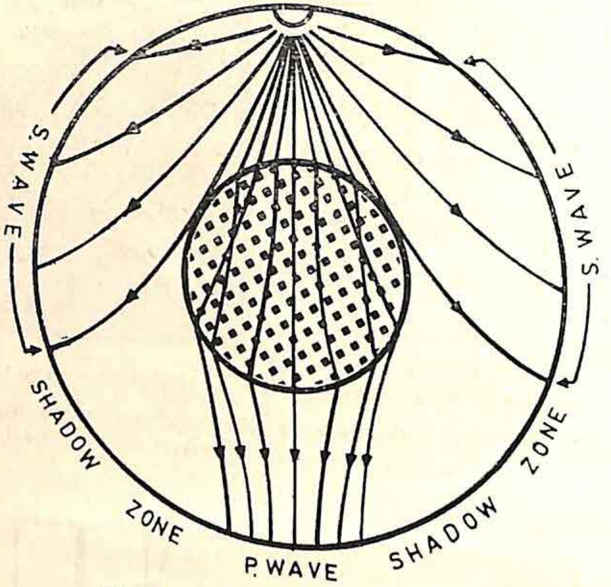

FIG. 3.4. Behaviour of *P* and *S*-waves.

they were much weakened and delayed. She postulated the existence of an inner core which could reflect the waves back into the shadow zones. This observation together with the velocity changes of *P*-waves in the core zone enables us to infer that the core also has two layers.

The knowledge that the earth contains a surface layer, *i.e.* the crust, was first recognised by A. Mohorovicic while studying an earthquake in the Balkans in 1909. He arranged all the nearby seismograph stations according to distances and thus could indicate the existence of a discontinuity by interpreting the travel-time curves. The base of the crust has ever since been known as 'Mohorovicic discontinuity' in honour of the discoverer. Several experiments have been carried out especially after the Second World War in different parts of the world to obtain independent results. In all these experiments a controlled energy source mostly by explosions was used so that the precise time and precise position of the source were known. The arrival time of resultant waves was recorded by a series of seismographs especially placed at known and at the same time at close distances along a straight line. The travel-time curves obtained by such experiments could confirm a boundary, between the crust and the mantle. Later, a German seismologist could detect two layers in the crust. The upper part of the crust became known as 'granite' layer and the lower as 'basaltic' layer. Now the granitic and basaltic layers are commonly referred to as sial and sima in geological parlance. The boundary between two is named as 'Conrad discontinuity' after the name of its discoverer. The average thickness of the crust has been calculated at about 50 km and that of sial and sima 16 km and 34 km respectively, except in mountainous regions. The method of measuring the thickness of the crust, sial or sima is again based on recording travel-time curve of reflected waves received by equally spaced seismographs.

THE INNER STRUCTURE

Based on the inferences drawn from the seismic data, the material constituting the earth is found layered into three concentric prominent zones, named as: (*i*) crust; (*ii*) mantle, and (*iii*) core. As indicated, the crust is found to extend to a depth of about 50 km from the surface and is further divided into two sub-zones, the sial and sima. Sialic mass consists of a mosaic of rocks and sedimentary beds with distinct elements. This conclusion is supported by geological and geochemical facts and geophysical investigations. Simatic mass, on the other hand, can be regarded as one homogeneous concentric layer in plastic or semi-plastic state but behaving like a solid. Seismic study further reveals that the sialic portion is not uniformly laid on sima but floats in it like an iceberg, so is the case of sima with the mantle. For example, lofty mountains like the Himalayas which are 8.84 km in height may have 7-8 times deeper roots inside the crust. The sialic portion is found to contain sediments and rocks rich in silicon and aluminium. On an average, it contains 65-75 per cent silica, the remaining material being mostly aluminium in some compounds. Hence, the upper layer of the crust is named as 'sial': si stands for silicon and al for aluminium. The sialic portion is represented by the most common rock types, *viz*. 'granite' and 'rhyolite'. The average density of the sial is calculated at 2.71 g/cc. In the simatic layer, silica decreases to 50-60 per cent and aluminium is largely replaced by magnesium with minor quantities of iron. Sima (silica and magnesium) is represented by the most common rock types 'gabbro' and 'basalt' at the upper level, and by olivine rich rocks and eclogites at the lower level. The average density of sima is placed at 2.9 g/cc.

From the base of the crust down to approximately 2,900 km there is a viscous plastic mass of composition similar to that of sima. It has been named the 'mantle' and has an average density of 4.53 g/cc. Below the mantle down to the centre is the core having a radius of 3,428 km. The entire core is believed to contain iron with minor amounts of nickel and cobalt in a metallic form, highly compressed due to the weight of superimposed mass. The presence of iron ore is proved by two basic facts. Firstly, the earth's behaviour as a huge magnet which is possible only by the presence of iron in the core. Secondly, some of the meteorites which are parts of heavenly bodies, have been found to be of the same composition. The density of the core is placed at 10.7 gm/cc which is again indirectly derived. Since the mean density of the earth is known, so also that of sial and sima, the densities of the core and mantle have been calculated using trial densities by averaging mass and volume of each concentric zone. A classical work of determining densities inside was of K.E. Bullen, an Australian seismologist. He based his interpretation (Fig. 3.5) on the basis of changes in the velocity distribution.

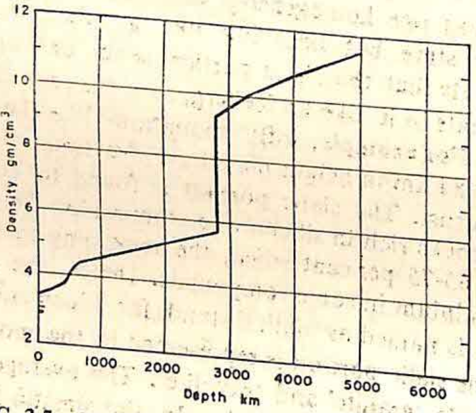

FIG. 3.5. Densities of various layers inside the earth.

The iron core is also divided into two parts, the inner and the outer core, as revealed from the behaviour of seismic waves. The outer core constituting the first 2,176 km below the base of mantle is inferred to be not in a solid state but something like a liquid. The inner core from this level down to the centre behaves as a solid mass. The seismic waves also reveal a different story about the narrow zone separating the outer and inner cores which has not yet been interpreted satisfactorily (Fig. 3.3).

COMPOSITION OF THE CRUST

Composition of the upper portion of the crust, *i.e.* the sialic portion has been determined by averaging the analyses of a large number of rocks exposed on the surface. From such analyses, it has been observed that 98 per cent of the upper portion of the crust is composed mainly of eight elements *viz.*, oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium and that two of them—oxygen and silicon—are far in abundance constituting together 74 per cent of the total composition; the remaining six account for 24 per cent (Table 3.1).

TABLE 3.1. AVERAGE COMPOSITION OF THE UPPER CRUST
(in per cent)

Oxygen	46.71
Silicon	27.69
Aluminium	8.07
Iron	5.05
Calcium	3.65
Sodium	2.75
Potassium	2.58
Magnesium	2.08
Titanium	0.62
Hydrogen	0.14
Phosphorus	0.13
Carbon	0.094
Manganese	0.09
Sulphur	0.052
Barium	0.05
Remaining elements	0.244

Out of 103 elements known so far (Table 3.2), only 90 elements have been found to be present in the crust in detectable quantities most of which are in a stable condition. The remaining 13 elements are unstable and have been recognised during the course of processing radioactive elements in the laboratory. Elements, by and large, do not occur in a free state but usually in a combined form according to their chemical affinities.

During the course of formation, a mineral acquires a definite crystallographic form depending upon the way in which the constituent atoms have arranged themselves. It also inherits a definite chemical composition besides some characteristic physical properties like hardness, feel, fracture sp. gr., etc. Nearly 2,000 minerals have been identified so far. Certain minerals falling under well-established groups like felspar, felspathoid, pyroxene, amphibole and olivine combine to form the most common rocks. The entire sialic portion of the earth's crust is thus an assemblage of minerals and rocks.

TABLE 3.2. NAME OF ELEMENTS WITH ATOMIC WEIGHTS

Element	*Symbol*	*Atomic Weight*
1. Actinium*	(Ac)	—
2. Aluminium	(Al)	26.98
3. Americium*	(Am)	—
4. Antimony	(Sb)	121.76
5. Argon	(Ar)	39.944
6. Arsenic	(As)	74.91
7. Astatine*	(At)	—
8. Barium	(Ba)	137.36
9. Berkelium*	(Bk)	—
10. Beryllium	(Be)	9.013
11. Bismuth	(Bi)	209.00
12. Boron	(B)	10.82
13. Bromine	(Br)	79.916
14. Cadmium	(Cd)	112.41
15. Calcium	(Ca)	40.08
16. Californium*	(Cf)	—
17. Carbon	(C)	12.011

Element	*Symbol*	*Atomic Weight*
18. Cerium	(Ce)	140.13
19. Cesium	(Cs)	132.91
20. Chlorine	(Cl)	35.457
21. Chromium	(Cr)	52.01
22. Cobalt	(Co)	58.94
23. Columbium or	(Cb)	—
Niobium	(Nb)	92.91
24. Copper	(Cu)	63.54
25. Curium*	(Cm)	—
26. Dysprosium	(Dy)	162.51
27. Einsteinium*	(Es)	—
28. Erbium	(Er)	167.27
29. Europium	(Eu)	152.0
30. Fermium*	(Fm)	—
31. Fluorine	(F)	19.00
32. Francium*	(Fr)	—
33. Gadolinium	(Gd)	157.26
34. Gallium	(Ga)	69.72
35. Germanium	(Ge)	72.60
36. Gold	(Au)	197.0
37. Hafnium	(Hf)	178.50
38. Helium	(He)	4.003
39. Holmium	(Ho)	164.94
40. Hydrogen	(H)	1.008
41. Indium	(In)	114.82
42. Iodine	(I)	126.91
43. Iridium	(Ir)	192.2
44. Iron	(Fe)	55.85
45. Krypton	(Kr)	83.80
46. Lanthanum	(La)	138.92
47. Lawrencium*	(Lw)	—
48. Lead	(Pb)	207.21
49. Lithium	(Li)	6.940
50. Lutetium	(Lu)	174.99
51. Magnesium	(Mg)	24.32
52. Manganese	(Mn)	54.94

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Element	*Symbol*	*Atomic Weight*
53. Mendelevium*	(Md)	—
54. Mercury	(Hg)	200.61
55. Molybdenum	(Mo)	95.95
56. Neodymium	(Nd)	144.27
57. Neon	(Ne)	20.183
58. Neptunium*	(Np)	—
59. Nickel	(Ni)	58.71
60. Nitrogen	(N)	14.008
61. Nobelium*	(No)	—
62. Osmium	(Os)	190.2
63. Oxygen	(O)	16.00
64. Palladium	(Pd)	106.4
65. Phosphorus	(P)	30.975
66. Platinum	(Pt)	195.09
67. Plutonium*	(Pu)	—
68. Polonium*	(Po)	—
69. Potassium	(K)	39.100
70. Praseodymium	(Pr)	140.92
71. Promethium*	(Pm)	—
72. Protactinium*	(Pa)	—
73. Radium*	(Ra)	—
74. Radon*	(Rn)	—
75. Rhenium	(Re)	186.22
76. Rhodium	(Rh)	102.91
77. Rubidium	(Rb)	85.48
78. Ruthenium	(Ru)	101.1
79. Samarium	(Sm)	150.35
80. Scandium	(Sc)	44.96
81. Selenium	(Se)	78.96
82. Silicon	(Si)	28.09
83. Silver	(Ag)	107.880
84. Sodium	(Na)	22.991
85. Strontium	(Sr)	87.63
86. Sulphur	(S)	32.006
87. Tantalum	(Ta)	180.95
88. Technetium*	(Tc)	—

Element	*Symbol*	*Atomic Weight*
89. Tellurium	(Te)	127.61
90. Terbium	(Tb)	158.93
91. Thallium	(Ti)	204.39
92. Thorium	(Th)	232.05
93. Thulium	(Tm)	168.94
94. Tin	(Sn)	118.70
95. Titanium	(Ti)	47.90
96. Tungsten	(W)	183.86
97. Uranium	(U)	238.07
98. Vanadium	(V)	50.95
99. Xenon	(Xe)	131.30
100. Ytterbium	(Yb)	173.04
101. Yttrium	(Y)	88.92
102. Zinc	(Zn)	65.38
103. Zirconium	(Zr)	91.22

*For these elements atomic weight has not been determined as yet.

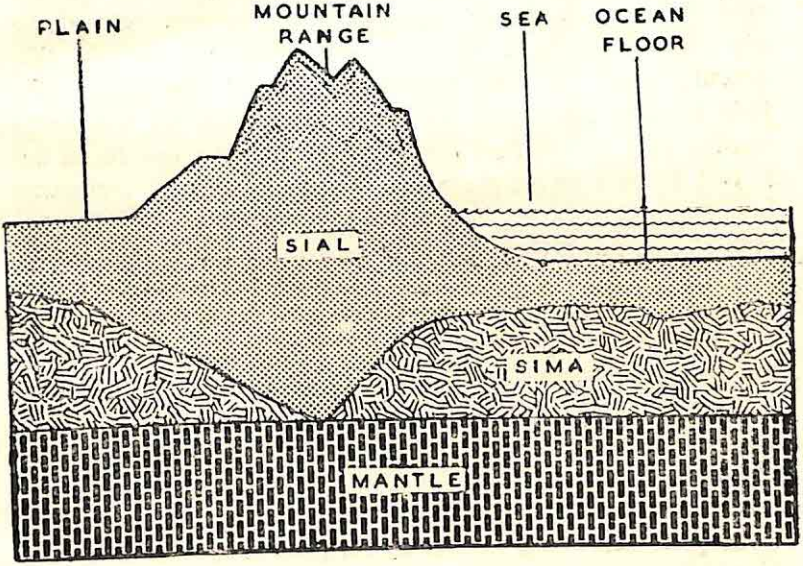


FIG. 3.6. Configuration of land (sial), sea and sima as revealed by seismic waves.

4

Geological Time Scale

In order to study the historical geology and the evolutionary part of the crust, a basis is required to be formed for measuring the time in absolute terms for the major phases that took place on the earth's surface. These phases or events can be anything inorganic or organic, starting from the emission of molten magma to stratification of rock beds, mineral forming activities, mountain building movements, growth of animal and plant life and similar other activities. In an attempt to evolve a time-pattern of events, the total time taken in forming the crust in the present form since its inception is divided into six eras, *viz.* Azoic, Proterozoic, Palaeozoic, Mesozoic, Tertiary and Quaternary. Azoic means an era without life; Proterozoic—era of the first life; Palaeozoic—ancient life; Mesozoic—middle life; Tertiary—new life; and Quaternary—recent life (Table 4.2). This broadly constitutes the major framework for measuring relative ages of the past geological events. An *era* forms the largest division on the geological time scale. A rock formation or a group of rock beds deposited in a particular era is put together as of one *group*. Each era is divided into a number of *periods*, and the beds deposited in one particular *period* is known as a *system*. A period is divided into *epochs* and each *epoch* subdivided into *stages*. A *stage* may be divided into *zones*. An age is the smallest sub-division in the geological time scale. It should be clear now that in the division of geological time scale into eras and in their further sub-divisions into periods, epochs and ages, a progressive growth of organic life has been taken as a basis. Progressive growth of organic life has proved to be of immense help in framing the geological time scale. The Cambrian period represents the earliest time in the geological history from which gradual evolution of animal and plant life has been traced. Although the existence of organic life is traced in the pre-Cambrian sediments also, it does not exhibit any hard part or changes that could be used in the time scale studies. Cambrian, therefore, is regarded as an index period in geochronology. On this basis, the time scale is divided into two broad divisions, *viz.* pre-Cambrian and post-Cambrian; the former being non-fossiliferous and the latter fossiliferous.

As indicated before, an era is the largest division in the geological time scale. The enormity of the time interval between one era and another is most significant. Each era ended in a sort of geological revolution which brought in abrupt changes of climate, lithology, biological growth and redistribution of land and sea. The end of an era was usually accomplished either by widespread volcanic activities or elevation of geosynclines into mountain ranges or both. Relative grouping and subdivision of post-Cambrian sediments, a beginning of the Palaeozoic era, are based entirely on the assemblages of fossils of like characteristics. While eras are separated by revolutions, periods are separated by major disturbances. These are similar to revolution, but the changes they produced on land surface, climate and forms of life are not so widespread or drastic. How organic life is an interesting aid in grouping and subdivision is described in detail in Chapter 5. The concept will become clear in Chapter 7. Sediments and rocks of pre-Cambrian eras are classified basically on field evidences like the order of superimposition, intensities of metamorphism, marked unconformities and change in lithological facies. These criteria are taken into account in classification of post-Cambrian sediments as well, including fossil assemblage.

AGE DETERMINATION BY RADIOACTIVITY

Measuring events in term of an absolute age became possible with the discovery of radioactive elements in 1896 and the rapid advances made in this field from 1902 onwards. The application of radioactivity to the determination of geologic age is based on the follwing facts:

(1) All radioactive substances possess the natural property of disintegrating continuously by emitting alpha, beta and gamma particles (atomic rays).

(2) The rate at which disintegration or decay proceeds is always constant and remains uninfluenced under all conditions. The rate of decay is independent of the original quantum of the radioactive substance.

(3) By the process of decay, all radioactive substances are finally transformed into stable radiogenic isotopes with a lower mass in comparison to their parent substance, the loss in weight being equal to the loss of alpha, beta or gamma particles.

(4) The time taken for a given quantum of the radioactive substance to disintegrate to one-half its original quantum always remains constant and is called the half-life value.

Nearly three hundred isotopes occur in nature of which the vast majority are stable. A small minority, however, decay spontaneously at constant rate into well defined end-products. These comprise:

(*a*) long-lived species like uranium and thorium isotopes,

(*b*) shorter-lived isotopes which are constantly being generated, and

(*c*) isotopes like C_{14} formed by cosmic radioactivity. Only long-lived species among the natural radioactive isotopes are of geochronological significance.

The half-life value of a radioactive substance has proved of immense value in age calculations. By half-life is meant that a given quantity, say a gm of U_{238} for example will disintegrate into half its original quantity in 4,560 million years (half-life year of U_{238}), half of the remainder in another 4,560 million years and so on till it is finally converted into a stable radiogenic isotope PbU_{206} with a total mass depletion of 32 in the form of He^+ as alpha particles (Table 4.1). It is a very definite characteristic of each and every radioactive substance. From Table 4.1 it may be clearly seen that uranium isotopes having atomic weight 238, 235 and 232 convert finally into radiogenic lead with atomic weight 206, 207 and 208 with corresponding mass depletions of 32, 28 and 24 in the form of He^+ (alpha particles). Emission of energy particles beta and gamma generally does not affect the mass. Radiogenic lead is different from common lead as found in mineral galena or cerussite. The atomic weight of common lead is 207.2.

Let us now suppose that an intruding magma has started cooling. The radioactive elements will also start segregating and crystallise as mineral constituents.

At the time of crystallisation, the minerals will have a pure radioactive element (*P*). With the passage of time, the daughter radiogenic isotope (*D*) is produced continuously and accumulated within the mineral. The proportion of *D*/*P* at any time in a mineral or rock sample provides a direct relation to the time that has elapsed in realising this proportion. If we are able to calculate the rate (*n*) at which *D* is being produced in a unit time, then

$$\text{Age of the rock sample} = \frac{D}{P} \div n \text{ years.} \qquad \ldots(1)$$

Alternatively, if the rate of change $P \rightarrow D$ is known, the proportion of *D* present will indicate the time (*t*) that has elapsed. Then, an equation can be constructed for dating the particular sample as under:

$$t = \frac{1}{\lambda} \log_e \left(1 + \frac{D}{P} \right) \qquad \ldots(2)$$

where λ is the decay constant of *P*.

In formula (1), *n* is calculated from the half-life time (*T*) value method after giving due consideration for depletion. The rate of decay λ is also determinable. The amount of *P* and *D* in a sample is measured by means of mass spectograph or stable isotope dilution analysis method. There is a distinct relation between the half-life value *T* and decay constant of a particular substance. As stated before all radioactive substances decay in accordance with the same law, only the value of decay constants differ for different substances. The law is represented by the formula:

$$\frac{N}{N_0} = e^{-\lambda t} \qquad \ldots(3)$$

where, *N* is the number of parent atoms left at any time *t*,

N_0 is the number to start with, and

λ is the proportion of parent atoms breaking down in a unit time, *i.e.* decay constant.

Fixing the condition of half-life in formula (3), we have:

$$\frac{N}{N_0} = \frac{1}{2}$$

or $$\tfrac{1}{2}=e^{-\lambda t}$$

Again substituting T (=half-life) for t, we have

$$2=e^{\lambda T}$$

or $$T=\log_e 2/\lambda=.6931/\lambda \qquad \ldots(4)$$

The half-life is inversely proportional to the decay constant and is independent of the initial amount of the radioactive substance.

TABLE 4.1. HALF-LIFE VALUES OF THE MOST COMMON RADIOACTIVE ELEMENTS USED IN DATING*

Parent element	*Radiogenic end product*	*Half-life years*
U_{238}	$Pb_{206}+8He_4+$	4.56×10^9
U_{235}	$Pb_{207}+7He_4+$	0.71×10^9
Th_{232}	$Pb_{208}+6He_4+$	13.9×10^9
Rb_{87}	Sr_{87}	60×10^9
K_{40}	A_{40}, Ca_{40}	1.33×10^9
C_{14}	N_{14}	5,730

*(*a*) An alpha (α) particle is composed of two protons and two neutrons tightly bond together, α-rays are deflected by magnetic field.

(*b*) Beta (β) particles are negative charge-electrons. They are easily deflected by magnetic field.

(*c*) Gamma (γ) particles are similar to X-rays. They remain unaffected by magnetic field.

(*d*) Radioactive elements are those which have unstable nuclei. They emit α, β, γ rays continuously at a constant rate.

(*e*) Isotopes are the atoms of same elements having different nuclear masses but identical atomic numbers.

One of the most common methods in use for dating rocks is the lead-uranium ratio method. It is precisely because the lead isotopes are more stable than other radiogenic isotopes used in geochronology. It is also because the decay constants of uranium and thorium are more accurately and reliably known.

Scientists in earlier years, therefore, based their estimations primarily on Pb/U values. Recently Rb_{87}/Sr_{87} and K_{40}/Ar_{40} ratio methods are also being applied as cross-checks. Calculation of ages of very recent years not exceeding 40,000 years is made by the C_{14}/C_{12} ratio method. This method is of great help to archaeologists.

Lead-Uranium Ratio Method

In this method, three different age ratios Pb_{206}/U_{238}, Pb_{207}/U_{235} and if Th is also present Pb_{208}/Th_{232} are independently calculated to ascertain if they are in agreement before the age measurement as a whole is considered acceptable. By and large, U_{238} is most abundant in an igneous rock mass. A gm of U_{238} finally converts into 0.865 gm of Pb_{206} and 0.135 gm of helium. From the half-life value, it is calculated that a gm of uranium will produce $\frac{1}{7600 \times 10^6}$ gm of lead per year. Then the age of a rock sample can be calculated as follows:

$$\text{Age} = \frac{\text{Amount of Pb present in the sample}}{\text{Amount of U present in the sample}} \times 7600 \times 10^6$$

years.

Carbon$_{12}$ and Carbon$_{14}$ Ratio Method

Normal carbon has an atomic weight 12, with six protons and six neutrons. The radioactive carbon has an atomic weight of 14, with six protons and eight neutrons. Every living being contains normal carbon. C_{14} is present there in a fixed ratio. This ratio has been determined as 0.01 mg of C_{14} in every 100 gm of normal C. When a living being dies, C_{14} starts disintegrating. Any quantity of C_{14} reduces to half in 5,730 years time. Thus, by analysing C_{14} content in a sample, the age of a given particular bed is determined in which a fossil is embedded. For example, let us take a fossil, which is analysed to contain 100 gm of normal carbon and 0.00125 mg of C_{14}. As it is known that originally 100 gm of normal carbon contained 0.01 mg of C_{14}; the same 0.01 mg of C_{14} will reduce to 0.005 mg in 5,730 years; 0.0025 mg in the next 5,730 years and to 0.00125 mg in another 5,730 years. Thus, the age of the fossil would be 17,190 years old. While determining the age by this method, it is not necessary to burn the whole fossil to calculate the carbon content, as it is not always possible to get the complete fossil of a plant or animal. A portion of it is burnt and the percentage of C_{14} in it is determined by a Geiger counter, an instrument used for measuring radioactive substances.

FIXATION AND CORRELATION OF THE AGE OF ROCK FORMATIONS

The relative age of various formations has been determined based on the ratio of lead/uranium values. The use of lead isotopes for dating the rock was first established by Nier. Nier's result was used by Holmes in 1947 to construct an absolute time scale as given in Table 4.2. Radiogenic method has made it possible to calculate the age of various formations including sedimentary rocks. The age of a sedimentary bed is determined by the relative disposition of the igneous mass. If an igneous mass is found intruding a sedimentary bed, naturally the latter would be older. If a sedimentary bed overlies the igneous intrusive bed, it would be definitely younger than the intrusive. By making a careful study of the disposition of sedimentary and igneous beds throughout the world, the age of individual formations, systems and eras has been ascertained. Radiogenic method suffers from some defects because this method does not indicate how long it took for a magma to crystallise and form the uranium minerals. Nevertheless, uptil now it is the only reliable method known for calculating the age of various formations. By lead/uranium method, the greatest age of a rock so far estimated is about 2,200 million years. Some of the rocks tested from the Republic of South Africa have shown an age of nearly 3,000 million years.

THE AGE OF THE EARTH

It is difficult to measure correctly how many million years have elapsed when the earth was formed as there was nobody to record the time. Some clue to the possible age is estimated from rocks available for inspection at the surface. Again, nobody could say for certain how many years the earth was in existence before the rocks were formed. The age of the earth has been determined approximately by dating the rocks and meteorites falling on the surface. The date determined from the radioactive substances found in the meteorites was found nearly

TABLE 4.2. GEOLOGICAL TIME SCALE

Era	*Period*	*Age in million years*	*Index fossils*
Quaternary	Recent		Living animals and plants. First appearance of man about six lakh years before.
	Pleistocene	1	Disappearance of many species of mammals.
Tertiary or Kainozoic or Cenozoic	Pliocene	13	Mammals, mollusca and flowering plants.
	Miocene	25	
	Oligocene	36	
	Eocene	50	
	Paleocene	60	
Mesozoic or Secondary	Cretaceous	140	Abundance of flowering plants. Disappearance of giant reptiles.
	Jurassic	180	First flowering plants.
	Triassic	240	Ammonites, reptiles, amphibia.
Palaeozonic	Permian	280	Disappearance of trilobites, gangamopteris.
	Carboniferous	350	Glossopteris.
	Devonian	400	Abundance of corals, brachiopoda, lung fishes.
	Silurian	440	Disappearance of graptolites.
	Ordovician	500	Abundance of trilobites and graptolites.
	Cambrian	600	Exclusively trilobites.
Proterozoic	Pre-Cambrian	1500	Possible beginning of life.
	Vindhyan		
	Cuddapah		
Azoic	Dharwar		
	Archaean	4000	Lifeless.

twice the age found of the rocks on the earth. Therefore, the earth is regarded as approximately 4,500 million years old, based on the age calculated from the meteorites. Astrophysicists believe that the Milky Way was formed some 10,000 million years ago, the sun having been probably formed 5,000 million years thereafter, half way through the life of the galaxy to which it belongs.

Prior to invention of radioactive method of dating rocks, the ages of rock systems were ascertained by a study of the rates of sedimentation and denudation. The age of the earth was normally calculated by dividing the total sodium content of the ocean by the amount of sodium entering them through river transport every year. Archaeologists were using ring-growth method in a tree for dating the ancient civilisation. But none of these method is perfect because of variant factors as at no time in the history of the earth's crust, the rate of denudation and sedimentation was uniform.

Radiometric method has provided the best tool in age determination. A vast amount of published data about the age determination being made available, it is now possible to evolve a very narrow age-range of different rock formations in a particular area. It is also now possible to divide the continent or a country by age provinces. Further work in this direction might reveal infra age pattern of various geological activities, leading to ascertaining precisely the various mineral-making epochs.

5

Geological Significance of Past Animal and Plant Life

The study of living animal and plant life is a subject matter of zoology and botany. A geologist is interested in studying remains, traces or imprints of animals and plants termed fossils, which are found preserved in the sedimentary rocks of past geological times. Such study forms an important subject namely, Palaeontology—a synthesis of palaeozoology and palaeobotany—which deals with the life of past geological times as revealed from fossil remains. Fauna and flora are the names given for animal and plant life characteristic of a region, period or geological stratum. Geologists take their help and utilise the evidences furnished by them in making stratigraphical studies. In this chapter we shall discuss how the evidences furnished by fossils provide invaluable help in studying the environmental conditions of the past, the changes that took place on the earth's surface and in stratigraphical study such as correlating and fixing the age of stratified beds formed in different areas. It is only by a study of the stratigraphical succession of fossil forms that the race-history of animals and plants (phylogeny) has been established with certainty.

It is a well-established fact that for existence of animal and plant life certain congenial environment is essential. In a particular environment, certain typical plants and animals took birth and grew luxuriantly. They died subsequently either their natural death or became completely extinct due to sudden changes brought about by diastrophism, and remained buried in the formation they grew. We are, here, not concerned with the millions of different lives that might have taken birth. More than 350,000 species of plant and 1,120,000 species of animal are known today. A palaeontologist is concerned with only those lives which had hard part and could leave remains or imprints. It is quite interesting to observe that fossils belonging to a particular species found occurring in a system of same age show marked similarity, although deposited in widely apart regions. They, however, differ perceivably in outer growth structure but without morphological changes, depending upon climatic conditions and areas of origin namely, the lakes, the fresh water or the sea. Marked morphological changes are, however, noticed in fossils of continental shelves (shallow water zone, 0-100 fathoms) than those of bathyal zone (intermediate depth, 101-1000 fathoms) and abyssal zone (deep seas from 1001 fathoms and below) because of adaptability to different temperature and pressure. Fossils of a particular age thus help not only in identifying formations of same age group, but also the area of deposition. Each group of sedimentary deposits, known as a *system*, is characterised by a particular assemblage of genera and species, which enable us to identify the system. In a similar manner, the small divisions—the *series* and *stages*—are each characterised by the presence of certain fossils which do not occur above or below. It is found further that the fauna of smaller division, namely, stages, is not of uniform character throughout; although there may be no change in the nature of the bed, some of the species and varieties which are abundant at one level become rare or disappear in passing to higher or lower horizon. A set of beds (stage) is thus divided into *zones*, based on the general aspect of the fauna which is different in each *zone*, but between these zones there will be no break either lithological and palaeontological. The stratigraphical classification of system, series, stage and zone is entirely based on palaeontological evidences. Once the order of succession of the formations in any area, newer resting on older, is established, it becomes fairly easy to correlate and fix age of respective horizons in other areas, however, disturbed it may be, by means of like fossil assemblage. Fossil is, and may be regarded as a geologist's clock by means of which he measures the time of past geological events.

There are certain classes of animal and plant whose families lived long and persisted from one system to another. At the same time there were certain classes which had comparatively short lives and found restricted to one period, epoch or age which serve us as index-fossil. Some species, as for example, graptolites and ammonites were so highly specialised in morphological characters and so restricted in range of time that they prove to be highly invaluable in making smallest subdivision of geological time. We shall read more about such index-fossils later and in this chapter. Lithology, order of superimposition and fossil characteristics are important documents which provide necessary data for correlating and fixing age of the formation. Geologists are engaged in such task for generations. Constructing bit by bit from such study, the past geological activities on the earth's surface have been unravelled, to a great extent.

CLASSIFICATION OF ANIMAL AND PLANT LIFE

In order to recognise fossils, a good knowledge of palaeontology is essential. Palaeontology itself is very vast and specialised subject, where one has to learn innumerable species and varieties. To understand palaeontology, it is necessary to have good idea of natural classification of animals and plants. In this classification, an attempt has been made to place together animals and plants under two major groups namely, Animal Kingdom and Plant Kingdom. Again, animal kingdom is put under two sub-groups, invertebrates (animals having no backbone) and vertebrates (animals having backbone, to this group human being belongs). Similarly, plant kingdom is put into two sub-groups, Phanerogams (higher plants) and Cryptogams (lower plants). Each group or sub-group is divided into phyla (races) which includes animals and plants believed to have descended from one ancestral stock. Each phylum is divided and sub-divided into smaller and smaller groups such as Classes, Orders, Families, Genera and Species.

A species includes a group of individuals very closely related to each other, having identical structural features. One species is generally distinguished from another by such characters as ornamentation, shape, relative proportion of parts and size. A species may have some variations because of physical and biological conditions under which they were living. Such variations are distinguished from other forms included in the species by some slight but fairly distinguishable modifications. A group of closely related species is called genus, a group of genera constitutes a family, related families are grouped under order, related orders in class, and related classes in phylum—the primary division of animal and plant kingdoms. To understand more clearly about this grouping, we may say a group of species such as tiger, lion, leopard etc. belong to one genus cat; and that of wolf, jackal etc. to genus dog. The whole classification is based on Darwin's theory of evolution.

In geological study, invertebrate faunas prove much more valuable than vertebrate or plant fossils because of their extreme abundance and colonisation. Among invertebrate kingdom, out of 21 phyla classified only 9 have proved to be of palaeontological interest because their species could leave hard parts. The remaining other phyla are useful for biological study mainly. In the natural classification given below, it is intended to describe only those phyla which have been found most useful in stratigraphical study.

PAST LIFE IN RELATION TO GEOLOGICAL FORMATION

The evidence of past life as known from the fossil record is established from Cambrian formations of Palaeozoic era, deposited some 600 million years ago. In the sedimentary facies of pre-Cambrian formations like Vindhyan and Cuddapah, the existence of life is not clearly established on fossil evidence. It might be that the animal and plant life which existed before the Cambrian period were so delicate and soft that they could not leave their imprints in the sedimentary rocks where they grew. In Cambrian period, we suddenly find a large number of invertebrate phyla chiefly Arthropoda, growing in abundance. This leads to the conclusion that life prior to Cambrian period existed as well. It is believed that algae and fungi, lower forms of aquatic plants, were in existence prior to Cambrian period, for it is considered that those microscopic plants were responsible for the formation of several sedimentary mineral deposits like iron ore, limestone and quartzite.

Cambrian period is known as the age of trilobites (Arthropoda). They make up more than half assemblage of fossils of Palaeozoic era. They grew under shallow and medium deep sea. *Trilobite* (Fig. 5.1) is a good indicator of an age. Wherever

TABLE 5.1. NATURAL CLASSIFICATION OF ANIMAL KINGDOM

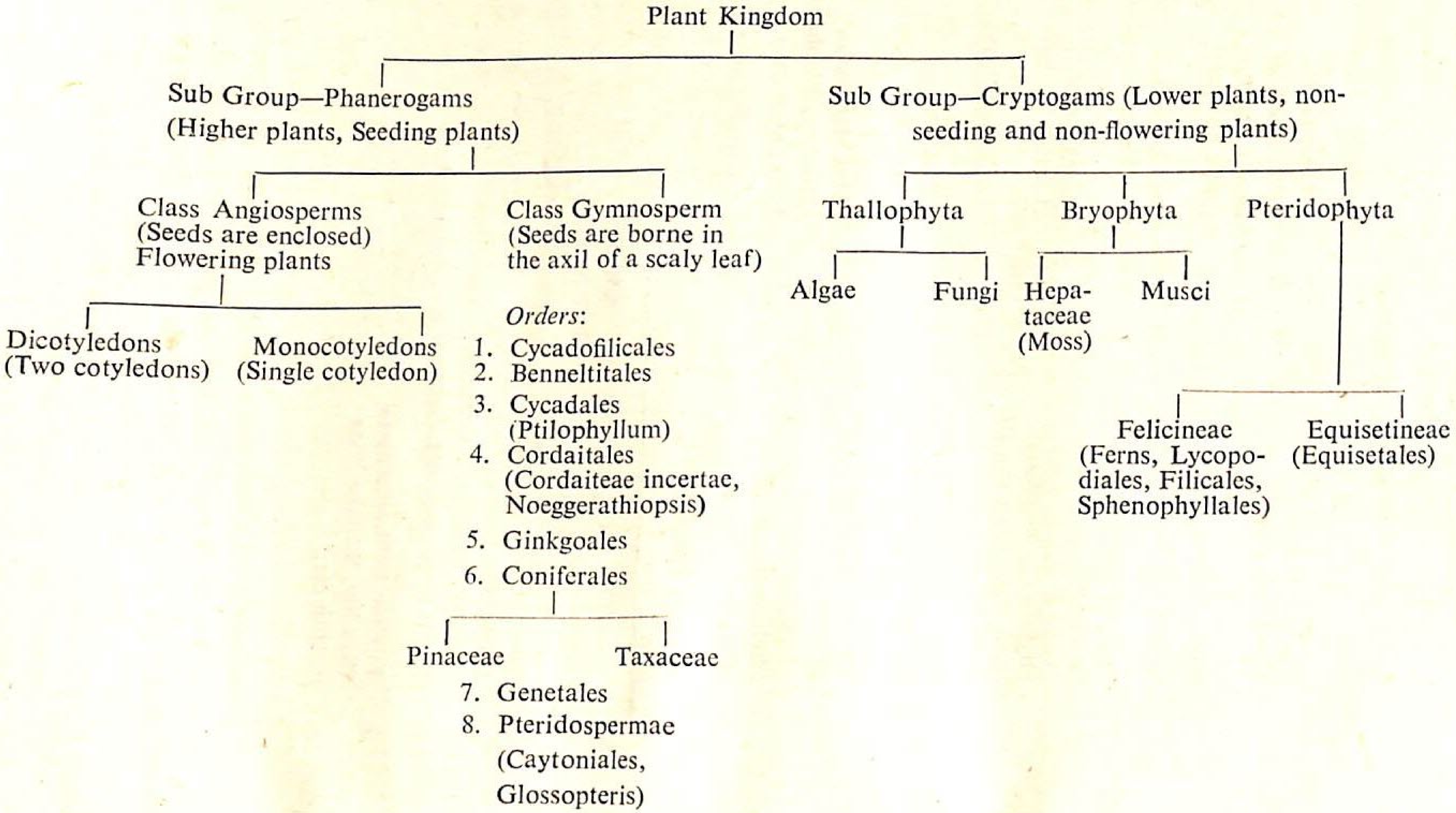
Animal Kingdom

- Non-Chordata (Invertebrate)
  - Phylum Protozoa (Single celled animals)
  - Phylum Porifera (Sponge)
  - Phylum Coelenterata (Jelly fishes and Coral)
  - Phylum Graptolithina (Graptolites now extinct)
  - Phylum Bryozoa (Sea Molasses)
  - Phylum Brachiopoda (Bivalve animals)
  - Phylum Mollusca
    - Class Lamellibranchia
    - Class Cephalopoda
    - Class Gastropoda
  - Phylum Arthropoda (Trilobites now extinct, Living Lobster, Crabs, Cockroaches, Grass hoppers, Ants, Bees etc.)
  - Phylum Echinodermata (Sea lily, Star fish, Sea urchin etc.)
- Chordata (Vertebrate) (Aquatic and non-aquatic animals)
  - Class Amphibia (Frog)
  - Class Reptilia (Lizard, Snake)
  - Class Aves (Birds)
  - Class Pisces (Fishes)
  - Class Mammalia (Monkey, Elephant, Lion, Man etc.)

trilobite is found in abundance, that formation is regarded to be of Cambrian period serving as good index fossil. They flourished throughout the Palaeozoic era with decreasing magnitude and became extinct completely towards the close of the era. In Cambrian formation we also find Brachiopods which are represented by fossils *obolus* and *lingula*.

The next succeeding Ordovician formation is distinguished from Cambrian by graptolites fauna which appeared and took

TABLE 5.2. NATURAL CLASSIFICATION OF PLANT KINGDOM



- Plant Kingdom
  - Sub Group—Phanerogams (Higher plants, Seeding plants)
    - Class Angiosperms (Seeds are enclosed) Flowering plants
      - Dicotyledons (Two cotyledons)
      - Monocotyledons (Single cotyledon)
    - Class Gymnosperm (Seeds are borne in the axil of a scaly leaf)
      - *Orders*:
        1. Cycadofilicales
        2. Benneltitales
        3. Cycadales (Ptilophyllum)
        4. Cordaitales (Cordaiteae incertae, Noeggerathiopsis)
        5. Ginkgoales
        6. Coniferales
           - Pinaceae
           - Taxaceae
        7. Genetales
        8. Pteridospermae (Caytoniales, Glossopteris)
  - Sub Group—Cryptogams (Lower plants, non-seeding and non-flowering plants)
    - Thallophyta
      - Algae
      - Fungi
    - Bryophyta
      - Hepataceae (Moss)
      - Musci
    - Pteridophyta
      - Felicineae (Ferns, Lycopodiales, Filicales, Sphenophyllales)
      - Equisetineae (Equisetales)

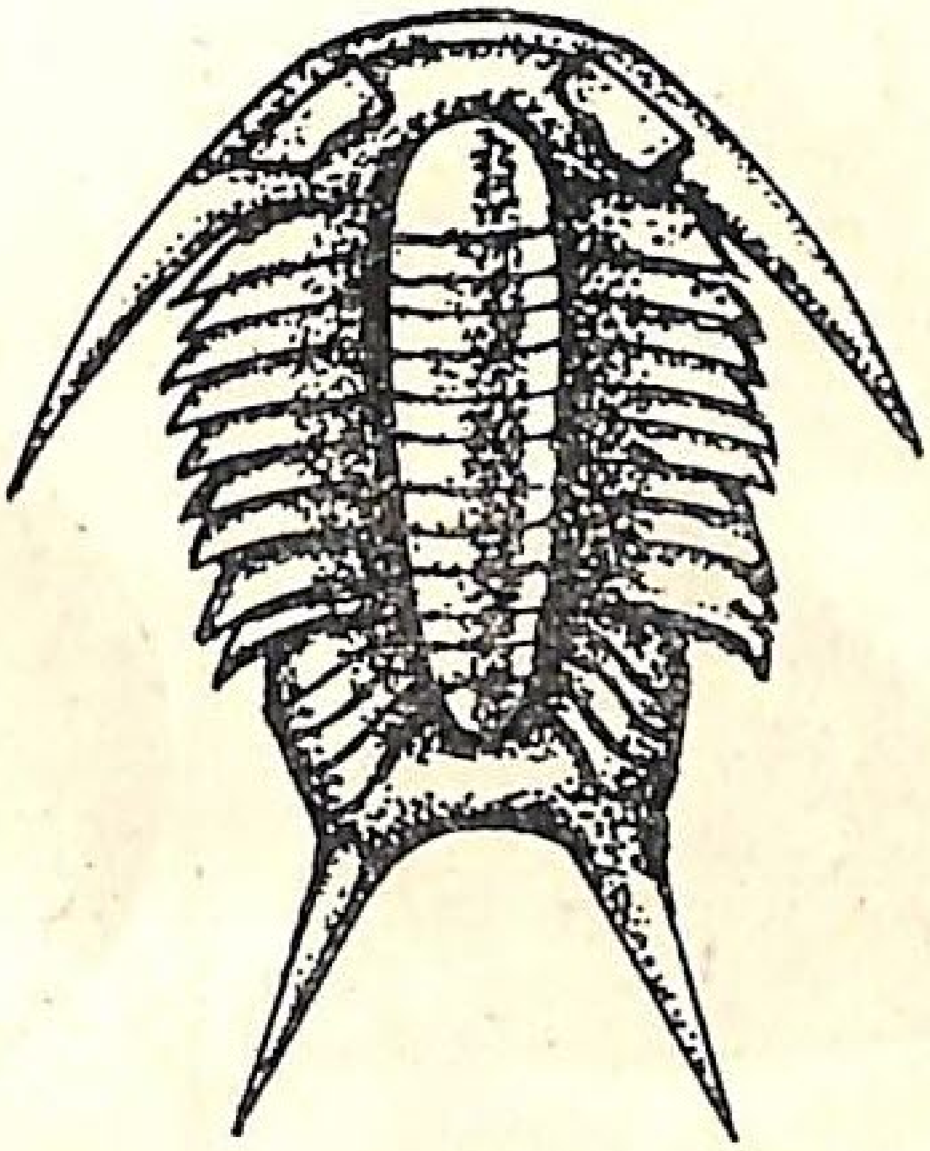


FIG. 5.1. Trilobite (Index fossil of Cambrian age).

tremendous development during the period and gradually became extinct before Devonian. Graptolite grew only in deep sea in shaly beds and lived in colonies. Ordovician formations in many parts of the world have shown traces and remains of the first true corals—honeycomb and horn corals; birth of first sea lilies (Crinoids), blastoides (now extinct) and the first star fishes (Asteroids) and appearance of first sea molasses (Bryozoa). Cephalopods became numerous in Ordovician. One particular species having straight uncoiled shell became abundant. Gastropods were minor in occurrence and simple in form.

In Silurian period, several Cephalopoda made first appearance of which ammonoids are most important. Corals became more abundant showing different varieties like honeycomb, cup, chain and compound corals which grew luxuriantly in shallow water. Corals are indicative of warm climate. Brachiopods began to appear in abundance, many new forms appeared in Silurian and in the succeeding periods. Brachiopods are best represented by Orthis and Spirifers. Crinoids, the echinoderma sea-lilies also attained their maximum development. All the major groups of mollusca are found in Silurian deposits.

The Devonian formations are characterised by the absence of graptolites and presence of new forms of corals (tetra-corals and tabulate coral). Devonian age gave rise to first fish the Ostracoderms and the first land vertebrates, amphibians, which belong to a group known as labyrinthodonts. The traces of first

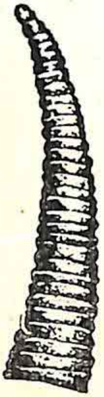


Fig. 5.2

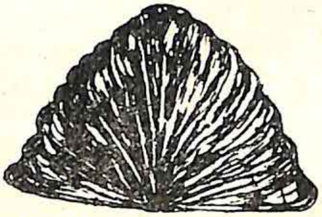


Fig. 5.3

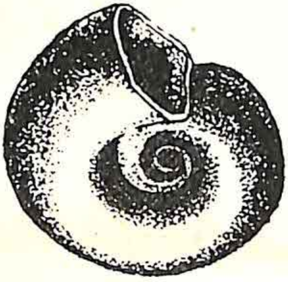


Fig. 5.4

FIG. 5.2. Cephalopod (Ordovician age).
FIG. 5.3. Brachiopod (Ordovician age).
FIG. 5.4. Gastropod (Ordovician age).

wingless insects are also found in the formations belonging to this age. There was climax in the development of gastropods. Cephalopods also appeared in exceeding quantities. The most important of Devonian age is the appearance of first land plants of which vascular plants, ferns and psilophyton (leafless) are important. Ferns grew as high as 10 to 12 metres.

The advent of Carboniferous period is marked by the abundance of sea lilies and thick vegetation—ferns and giant size scale trees—lepidodendron (Fig. 5.7) and sigillaria (Fig. 5.5) attaining height of 30 metres. The beds of lower Carboniferous age show abundance of fossils of shark fish. During the same period, honeycomb corals practically died out. Fusulinids became abundant in upper Carboniferous and became extinct in Permian. The upper Carboniferous formation show remains of reptiles and snails—the first gastropod to live out of marine environment. More than thousand varieties of cockroaches are recorded in the rock types of upper Carboniferous. There was abundance of labyrinthodonts during this period. The classification of lower and upper Carboniferous deposits is made by intervening glacial boulder beds as of Talchir age in India, and throughout Gondwanaland.

On the other hand, the division of lower and upper Gond-

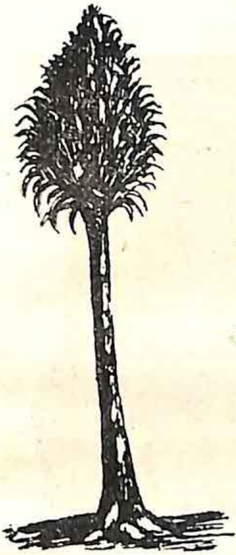


Fig. 5.5

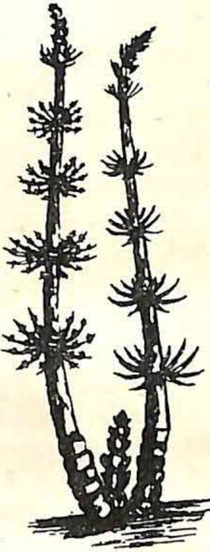


Fig. 5.6

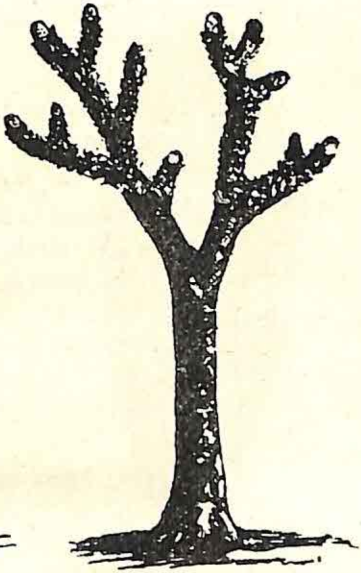


Fig. 5.7

FIG. 5.5. Sigillaria (such plants grew during Permo-Carboniferous age in Western Europe and USA and found abundantly in Coal Measures).

FIG. 5.6. Calamites (such plants grew during Permo-Carboniferous age in Western Europe and the USA and found abundantly in Coal Measures).

FIG. 5.7. Lepidodendron (such plants grew during Permo-Carboniferous age in Western Europe and the USA and found abundantly in Coal Measures).

wana is based entirely on plant fossils. In lower Gondwana, the most characteristic plant fossils are pteridospermae, a fern-like seeding plant (species *Glossopteris*) and cordaitales (species *Noeggerathiopsis*) of higher plants, and equisetales (species *Schizoneura*) of lower plants. In upper Gondwana, glossopteris disappears and there is an advent of a new plant ptilophyllum of class cycadales (Cycophyta). Ptilophyllum is characteristic plant fossil of upper Gondwana. In Permian period, a group of carnivorus reptiles (Theriodonts) are found to appear, the first animals having teeth like those of mammals. The invertebrate

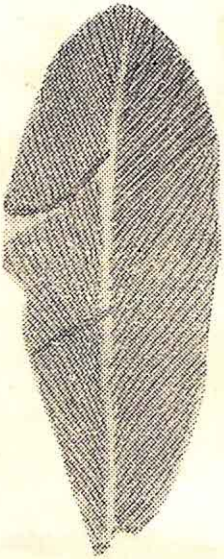


Fig. 5.8

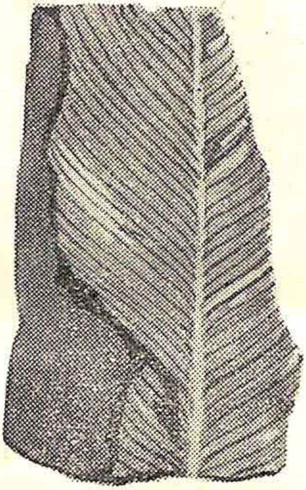


Fig. 5.9

FIG. 5.8. Glossopteris (an indicative of lower Gondwana formations).
FIG. 5.9. Ptilophyllum (an indicative of upper Gondwana formations).

faunas trilobites and fusulinids completely became extinct; and cephalopods chiefly ammonoids became more important and increasingly specialised. The luxuriant growth of trees which were responsible for coal formation began to decline by the end of Permian.

The next succeeding era—Mesozoic—had three periods of deposits *viz*. Triassic, Jurassic and Cretaceous. On the whole, Mesozoic is regarded an era of giant reptiles. Throughout Mesozoic, sea and land reptiles practically ruled all over the globe. In Triassic formation, the evidence of first dinosaurs and theromorphs is recorded. In open oceans, dolphin like ichthyosaurs swept through the water. Later 4 to 6 metre long plesiosaurs paddled their way through Triassic seas. Among invertebrates marine animal ammonoids (Cephalopods) became most important. The suture patterns in the ammonoids tended to become increasingly complex. Ceratites are the most representative ammonoids of Triassic age; among brachipods, spirigera and shiriferina, and among lamellibranch, myophoria, avicula and ostrea are the most representative. For the first time sea urchins (Echinoids) made appearance. The tetracorals and honeycomb corals which died out in Permian were supplanted by hexacorals. The appearance of first lobster and shrimp like animals is seen in Triassic formations. Ammonoids became extinct towards the end of Triassic except two genera phylloceras and belemenites which survived into Jurassic. Scale tree and seed tree ferns were very rare in Triassic. In Jurassic, there were great many developments in the giant reptiles. Three main groups of reptiles are noted: (*i*) long necked, long tailed, four legged—sauropods monsters; (*ii*) armoured reptiles--stegosaurs that weighed up to 10 tonnes, and (*iii*) the carnivorus—theropods which walked on their hind legs. Ichthyosaurs and plesiosaurs were the carnivorous monsters of the oceans. For correlation of formations, however, ammonoids play an important part because of their great variety and short time-range of the species. Belemenite are the characteristic fossils of lower Jurassic which lasted up to upper Cretaceous. Radiolarian (Protozoa), sponges (Porifera, pore-bearers) and crinoids (Echinoderma) and hexagonal corals were widespread in Jurassic. Protozoa gave rise to radiolarian cherts, and echinoderms—the crinoidal limestone. Vast deposits of such siliceous (cherty) and crinoidal limestone beds are found in the formation of Jurassic period. The evidence of first flying bird called Archaeopteryx is found in this period. Jurassic plants included cycads, conifers, firns and ginkgos. Ginkgos were widespread throughout Mesozoic but later became almost extinct.

The Cretaceous period was marked by the arrival of flowering plants (Angiosperms) and became dominant plant on every continent. The familiar living trees and shrubs *viz*. poplar, oak, magnolia, maple, beech etc. appeared during this period. Foraminifera play an important part in Cretaceous stratigraphy. Many of their species have been used as index fossils. Orbitolins of genus orbitoids are characteristic fossils of lower Cretaceous, forming coastal reef and reef facies. Calcareous and siliceous sponges occur in the middle Cretaceous. Among the Echinoderms, the genera of echinoids such as discodea, cidaris, holaster etc. are useful in classification of stages. This period is singularly important for being fore-runner of the mammalian confirms that the moon originated in the same manner as other planets. It provides a valid proof that tidal waves generated by moon might have been the real force in piling up the sialic mass in earlier times.

GREAT DEPRESSIONS

The study of the early history indicates that, during the post-Vindhyan period, a great depression (geosyncline) was formed in the earth surface covering north-west Africa, Spain, Alpine-Himalayan range of today extending up to island arc of Indonesia and New Guinea. This depression is named as Tethys sea which became the seat of depositions from Cambrian to the end of the Tertiary era. The Tethys sea virtually separated the globe into two super continents, the southern and northern. The southern land mass is known as Gondwanaland which consists of India, Australia, Antarctic, Africa, Malagasy and South-America. The northern land mass is known as Laurasia, Eurasia and Angara-land. The Laurasia consists of North-America and Greenland; and Eurasia and Angaraland consist of the land masses west and east of present Ural mountain range. In the Silurian period, another Mediterranean geosyncline was formed, as a result of Caledonian mountain building forces, which extended from south-west England through France and Central Europe into Mediterranean area, mixing with the Tethys sea with a branch extending into Russia, forming the Ural geosyncline and Moscow basin. On the whole, by the beginning of Palaeozoic era, the land mass north of Tethys sea was largely submerged under sea whereas the southern mass was not inundated by the sea.

MOUNTAIN BUILDINGS

There are distinct evidences of several orogenic (mountain building) movements in the past both in pre-Cambrian and post-Cambrian eras. Each orogenic movement was accompanied by lifting, folding and faulting of weak zones like geosynclines and basins, coupled with widespread intrusive and volcanic activities.

The earliest tectonic movements in India are recorded during post-Dharwar and post-Vindhyan periods which folded the

Dharwar and Cuddapah rocks and gave rise to Aravalli mountains for a whole length of Rajasthan in north-east and south-west direction. Aravalli mountain in the west and eastern ghat stretching through coastal region in the east are the finest example of relict mountains in the world. Between Dharwar and pre-Cambrian three periods of profusely igneous intrusive activities are recognised affecting largely the structure and composition of original rocks. From Cambrian to recent times, four distinct mountain building periods are recognised *viz.* (*i*) Caledonian orogeny in Silurian period, (*ii*) Hercynian orogeny in Permian. This orogeny is also known as Armorican or Variscan chains. (*iii*) Cimmerian orogeny in Jurassic period, and (*iv*) Alpine-Himalayan orogeny throughout Tertiary era.

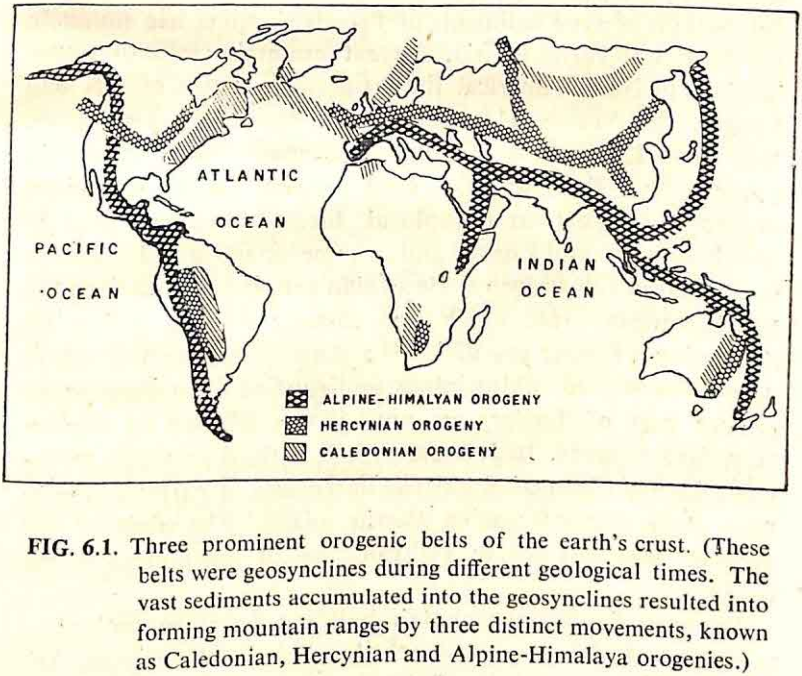


FIG. 6.1. Three prominent orogenic belts of the earth's crust. (These belts were geosynclines during different geological times. The vast sediments accumulated into the geosynclines resulted into forming mountain ranges by three distinct movements, known as Caledonian, Hercynian and Alpine-Himalaya orogenies.)

Caledonian orogeny affected northern mass beyond Tethys mainly which resulted in raising land above, forming inland lagoons and shallow water lakes which later became the seat of red sandstone formations. Hercynian orogeny took place in three phases—early, middle and at the end of Permian period. In the middle Permian, Hercynian mountain building movements took place affecting North America, south-west England, France and Germany, making the mountain range trend north-west and south-east (Armorican chain). The same Hercynian orogeny affected Central Europe making the mountain range trend north-east and south-west (Variscan chain). Moscow basin and Ural geosyncline were folded during the early Permian, and a mountain range rose from the troughs spreading out sediments into the adjacent shallow seas and low lying areas. The vast plains between Moscow basin and Ural mountain range are occupied by Permian sediments. Finally, towards the end of Permian, all of Russia emerged as continuous land extending across the continent of Asia which was up to that time been divided by the waters occupying the geosynclinal troughs. Beautiful sections of type sediments of Permian system are found in the district of Perm, Russia. A great mountain range of Appalachians of North America, the Armorican chains of UK and France, the Vosges, Harz mountains, the Urals, Tien Shah, Kun lun, Karakoram, Tsinling and many other ranges in Central and Eastern Asia were formed during Hercynian orogeny. A great stratigraphical break which is found in North America and Europe and to some extent in India also is as a result of this orogeny. Hercynian orogeny also affected the Mediterranean area, which was already marine region, by depressing it further and giving it a shape of geosyncline; where deposition started taking place undisturbed from Permian to greater part of Tertiary era until it was affected by Alpine-Himalaya orogeny. In Jurassic period, a third orogenic movement namely Cimmerian was felt in the area of extreme South-East Asia circumferencing Pacific ocean. The effect of this orogeny was not felt in Tethyan zone or other areas of the world.

The most significant mountain building movement took place in Alpine-Himalaya region which continued throughout the Tertiary era punctuated by intervals of comparative quiescence. A beginning of this orogeny was made in the upper Cretaceous which started with widespread lava flows in the Gondwanaland. The entire Alpine-Himalayan basin was affected by 4-5 orogenic cycles. The first orogenic movement was started, as mentioned above, in the upper Cretaceous affecting Mediterranean region, compressing and shallowing the Tethys sea in that area. The second movement was in the upper Eocene which mostly affected the Himalayan region. A strong orogenic movement occurred in middle Miocene affecting the entire Alpine and Himalayan range. During this time, the Tethys sea became completely shallow, the thick sediments deposited into it since past geological ages were compressed and turned into mountain ranges. With the close of Pliocene, there were again mountain building movements in Alpine-Himalayan region which folded, faulted and moved the huge masses several kilometres away forming the nappe structure (movement of folded and faulted mass along a low angle fault plane for a considerable long distance). High altitude of various mountain ranges which we find on Himalaya today is due to nappe structure. The core of the central Himalaya consists of crystalline mass which is formed due to intrusion of granite mass during the Tertiary orogenic periods. This mountain building force brought into existence several mountain high ranges which include the Atlas (North Africa), Pyrenees, the Alps, the Caucacus, the Himalaya and the Malaya Arc. The same forces lifted the shallow basins of North America and South America forming Rockies and Andes mountains on the west coast bordering Pacific ocean; and also resulted into giving birth to several depressions later forming inland seas like Caspian and Black sea.

GLACIATION PERIOD

Like mountain building forces originating in different periods the earth's crust has similarly witnessed formation of thick ice sheets from time to time in the geological past. Four such events are recognised: (*i*) in pre-Cambrian; (*ii*) in the beginning of Palaeozoic era; (*iii*) in Carboniferous period; and (*iv*) in Pleistocene period. These events again, like mountain building, were not universal but were confined to certain part of globe covering wide area depending upon the then wandering equator and altitude. The glaciation periods are recognised by studying typical deposits formed by glaciation *viz.* moraines or tillites. Moraines consist of rounded pebbles with striation marks, caused by sliding against other rocks, enclosed in clayey matrix. Sediments of pre-Cambrian moraines have been found at Spitzbergen in Norway, in north-east Greenland, near the mouth of Lena river in Siberia and at some places in Australia and in the Republic of South Africa. A second spell of the event is recognised during the early Palaeozoic era. The moraines of second glaciation period are found mainly in Katanga, Africa and perhaps in China. The evidences of the third glaciation period in Carboniferous period are more profound than the previous two. It has been well established that the dawn of Gondwana period, as we shall study in Chapter 7, began with glacial deposits. During those periods most of the Gondwanaland was covered under thick ice sheets and with the environmental changes, the glaciers started melting giving rise to several metres thick moraine deposits. The last of the four glaciation periods started in Pleistocene time which is still persisting as we find thick sheets of ice covering both Arctic and Antarctic regions. In the Arctic regions, it is estimated that the ice sheet more than 3 km thick is perpetually covering over the surface of the sea and land areas around it. Let us imagine what will happen if these ice sheets start melting. It will result into pouring more water in the sea thus engulfing more land mass. Presently only 1/4 of the surface area of our earth is land mass and remaining 3/4 under water and if ice sheets of north and south polar regions and those capped over high altitude mountains melt away, the earth surface will be submerged further to a great extent. Submergence of land areas under sea is not uncommon. Several evidences of encroachment of sea over the land surface are found in the history of earth's crust.

CONTINENTAL DRIFT

One of the most significant events on the earth's surface has been rifting and drifting of the continents from each other. It has been discussed earlier that in the beginning the earth's crust was one continuous land mass, named Pangea, Greek word meaning one mass. Palaeography of the earth surface reveals that till Jurassic time all the land mass was together, it then started rifting and drifting. Rifting was more or less complete by the end of Cretaceous period. The separation as per the geological evidences like similarity of coastal rocks and flora and fauna, began first with gigantic rift in Jurassic forming Africa and South America and Antarctica and Australia masses. India was separated from Africa towards close of Cretaceous and started moving north, bolting the Tethys sea. The bolting of India caused great compression, squeezing in the vast sediments deposited in Tethys sea into a great mountain range. North America drifted north-westward. Eurasia and Angaraland moved slightly towards north. South America broke loose and drifted westward while Greenland and Europe parted. The last two continents to drift away were Australia and Antarctica. Remaining piece of land of Africa moved north bolting the Mediterranean geosyncline. America, Australia and Asia moved towards each other across the vast Pacific ocean compressing the sediments piled up in the coastal basins to form the Andes of South America, Rockies of North America, the Inland arc of the Aleutians of Japan and the other Archipelago of the Western Pacific. The widening distances between the continents gave rise to vast oceans.

Rifting and drifting of continents from Pangea is no wonder. Just as an iceberg floats in the sea, the upper layer of the crust floats on the denser layer sima, which is more or less like a plastic mass. The land masses now forming the continents apparently slid along different weaker zones of the simatic layers, suggesting that the layers are placed one upon another like plates. The same phenomenon explains how the continents and the oceans were formed and also why the floors of different oceans have different depths. The maximum depth of the oceanic bed recorded so far, 10.6 km, is in the Pacific ocean, off the island of Marianas in the Philippines. The shallowest trench (ocean valley) in the Pacific ocean is about 6.67 km deep. The maximum depth of the Atlantic ocean is near the Puerto Rican Coast (26°N 67°W) measuring 9.21 km; the shallowest Atlantic trench measures about 5.68 km. The deepest trench measured in the Indian ocean is near Wharton (18°S 102°E) which is about 6.66 km deep; the shallowest trench is 5.57 km. Thus, the Pacific ocean is the deepest, and the Atlantic comparatively deeper than the Indian ocean. The depths of oceanic floors too are, therefore, not uniform, as they have slide on different plates. A distinction can be made between the continental crust which is broadly granitic (sial), and the oceanic crust which is basaltic in composition.

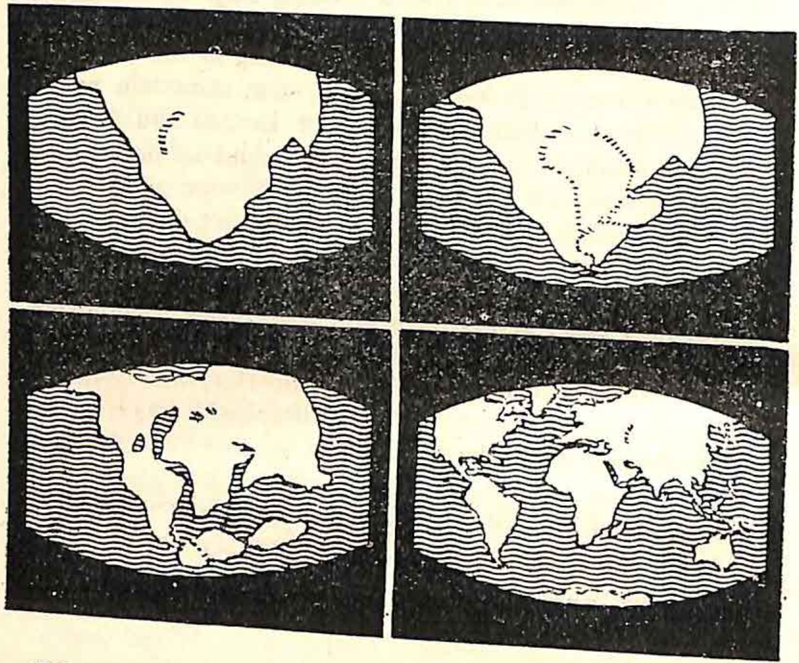


FIG. 6.2. Continental Drift (These four sketches show rifting and drifting of continent during different geological periods: (1) configuration of land mass prior to Jurassic period, (2) during Jurassic period, (3) during Cretaceous, and (4) the present distribution of continents.

What force made them split and drift is still a matter of great scientific investigation. The great volcanic eruptions and the forcing up of the molten magma in the past might be the cause of gigantic rifts and generating necessary forces for drifting the rifted sialic mass. Volcanic eruptions arising from below the ocean beds are still going on. Such eruptions forming great mountain ranges are found on the oceanic floors in several areas of Atlantic and Pacific, as discovered by oceanographic survey. The mid-Atlantic ridge is entirely made up of eruptive mass. Drifting of continents is an established fact based on the geological evidences. The continents are still moving. It has been calculated in recent years that the Atlantic ocean is widening at the rate of 2.5 cm per year and Australia is heading towards India at the rate of 5 cm per year. One of the causes of the frequent snapping of telephone and telegraph wires laid between the continents is the continued drifting of the continents.

The observations have indicated that there is a fundamental difference in the movement of the continents bordering Pacific ocean and that of Atlantic and Indian oceans. Below the Pacific and Indian oceans there are active plates—deep extensions of the continents—scraping against each other i.e. they are in direct collision. In the Atlantic the plates are moving apart (rift plates). Around the Pacific the plates in collision push one another down into the magma causing earthquakes.

What is the significance of these plate tectonic processes in our search for mineral deposits? The significance is, indeed, far-reaching. Minerals are normally formed from magmatic materials (magma refers to the molten rocks inside the mantle) and their location depends to a large extent on where and how far the magma has been pushed up to the sial. This pushing up was due to several kinds of geological activities in the past which were connected with the sliding of land masses. This is where plate tectonics theory comes in. This theory clearly suggests that these plates, the weaker zones which may be regarded as being in the plastic or semi-plastic state (thus giving rise to the sliding of continents), could not have been congenial to allow magma to crystallise and form mineral deposits. Magmatic deposits require a suitable temperature and pressure to form a mineral. The magma, in fact, must move up above the plastic zones to give rise to mineral deposits. It leads us safely to conclude that the possibility of finding mineral deposits is limited mostly to the upper half of the sial, whether on land or areas submerged under the sea. In general, it may not be possible to encounter mineral deposits at depths below 8 km. The geothermal gradient may be taken as another factor preventing the formation of mineral deposits beyond that depth.

7

Geological Formations

The oldest rocks covering the earth's surface are grouped under Azoic. The rocks of this era are termed Archaean and are represented by rock types granite, gneiss and schists, a true representative of sialic portion. Almost at all places these have undergone so much change, due to plutonic intrusions and subsequent metamorphic actions that it found convenient to designate them as basement complex. For a vast period of time, Archaeans were subjected to erosion. Several highlands were brought to peneplaination, thus providing sediments for new formations in succeeding eras. Metamorphosed sediments of Archaeans mixed with original rocks are referred to Dharwar system. The line of differentiation between Archaean and Dharwar is not so subtle as is available in formations of younger ages. Therefore, some authorities prefer to regard Dharwar and Archaean together. The name Dharwar system has originated from Dharwar district where it was first studied. Dharwarian period is marked by several plutonic activities. The original rocks were injected profusley by molten magma rising from below. Both Archaeans and Dharwars are the homes of varieties of useful metallic and non-metallic minerals, ores and rocks, *viz.* ores of copper, lead, zinc, manganese, iron, tungsten, radioactive minerals, mica, apatite and rock phosphate, and several building stones including marble and slates. The great iron ore series containing vast deposits of iron ore, and Sausar series of Madhya Pradesh and Maharashtra containing manganese ores and several other deposits found elsewhere belong to Dharwar system.

Sedimentary facies of Archaeans, giving rise to distinctly recognisable systems, are named as Cuddapah and Vindhyan. These rest on the denuded surfaces of Archaeans. A vast time must have elapsed before Cuddapah and Vindhyan were laid.

Cuddapah and Vindhyans are the extensive source of limestone, dolomite, sandstone and quartzite. Quartzite rocks of Vindhyan are friable and used as silica sand for glass making. Vindhyan, in addition, is a source of diamond bearing conglomerate deposits. The middle of Vindhyan period witnessed two separate cycles of volcanic activities erupting kimberlite lava which is the source of diamond. Each cycle happened after a long interval of time, thus, giving rise to two diamondiferous conglomerate beds. Kimberlite pipes intruding Vindhyans are the original source of diamond. The conglomerate beds were formed by denudation of kimberlite pipes and surrounding rocks, thus, accounting for a secondary source of diamond. Diamond bearing kimberlite pipes of equivalent age are mined at several places in the Republic of South Africa, Tanzania, Congo and elsewhere in Africa. It appears that volcanic eruptions pouring out kimberlite type lava were mostly confined to African continent.

Sediments of Cuddapah and Vindhyan are found to attain thickness of 6,000 metres and 3,200 metres respectively in the areas where they are well developed. One can very well imagine the time that must have been taken in depositing such a vast thickness of sediments.

Cuddapah was subjected to much tectonic movements. The formations of this system are, therefore, folded, faulted and recrystallised. Such effect is not found on Vindhyan. Different beds lie almost horizontal maintaining their original deposition characters. The only locality where the Vindhyan strata show any marked structural disturbance is along south-east edge of Aravalli mountain. Cuddapah system is quite perceivable in Cuddapah district of Andhra Pradesh, Chattisgarh of Madhya Pradesh and Gangapur in Orissa. Formations equivalent to Cuddapah are called Delhi system and that of Dharwar, Aravalli system in Rajasthan. Vindhyan system has derived its name from Vindhyan mountains extending from Dehri-on-sone in Bihar to Hoshangabad in Madhya Pradesh and Chittorgarh in Rajasthan to Gwalior in Madhya Pradesh extending up to the border of Agra. Deposits equivalent to Vindhyan are known as Kurnool system in South India, providing a good source of limestone, sandstone and quartzite. Some sandstone deposits of this system especially of Bhander stage show deep and attractive colours. They are used extensively for decorative building stones. Lower Kaimur series occurring at Amjhor near Dehri-on-sone contains a pyrites bed of about one metre thick associated with shale. Pyrites is an ore of sulphur. Amjhor deposit is the largest known source of pyrites in India, besides at Saladipura in Sikar district, Rajasthan.

TABLE 7.1

Succession of Vindhyan formation in India	*Maximum thickness recorded*
Bhander series—arenaceous and calcareous *Unconformity*	450 metres
Diamondiferous conglomerate *Unconformity*	
Rewa series—mainly arenaceous *Unconformity*	300 metres
Diamondiferous conglomerate *Unconformity*	
Kaimur series—mainly arenaceous *Unconformity*	390 metres
Semri series—calcareous and argillaceous *Unconformity* Archaeans.	900 metres

Arenaceous type sediments give rise to the formation of sandstone, further recrystallisation and pressure transform them into quartzite. Argillaceous and calcareous sediments, on the other hand, form shale or phyllite and limestone, respectively.

Some of the sediments of upper Vindhyan are reported to contain traces of fossils indicating origin of first life on the earth. In between the close of Vindhyan system and Cambrian, the lowermost system of Palaeozoic era, for a period of about 900 million years, there existed what is known as Proterozoic era. This long interval of time brought revolutionary changes in environment, for suddenly Cambrian formations are found to contain abundance of fauna. It is clear that the climatic condition prevailing in the period preceding Cambrian must have become quite suitable for the existence of life. It is, therefore, believed that the Proterozoic era was responsible for the creation of early life. Thick deposits of conglomerate, quartzite, slaty shale, tillite found lying below Cambrian formations separate Proterozoic from Palaeozoic.

In spite area of Kangra district, a complete formation for Cambrian to Recent is found which is the classic ground of geologists, for study. Cambrian system is well developed in Northern Europe bordering Baltic sea, Mediterranean region, Poland, Wales in England, and elsewhere. Salt range situated in Pakistan is a typical representative of Palaeozoic formations.

It is noteworthy that Peninsular India was not receptive to deposits of Cambrian to lower Carboniferous for nearly 2/3 of the Palaeozoic period, as it was having a gradual uplift during those periods. Most of the younger formation from upper Carboniferous are lying either on Archaeans, Cuddapah or Vindhyan in Peninsular India. Deposits of early Palaeozoic period took place mainly in Himalayan region and beyond north. Isolated deposits of inland seas of pre-Cambrian era are found in western Rajasthan giving rise to phosphorite deposits. By and large Cambrian to lower Carboniferous formations are found in the areas covering Tethys sea and land mass north of Tethys sea, with the exception of Tasmania depressions and western Australia in the southern land mass. In the depression south of MacDonnel Range, over 1,800 metres thick sediments of Ordovician sandstone, shale and limestone are found. In African continent, the areas situated south of equator, is found practically devoid of geological horizons from Cambrian to lower Carboniferous. Cambrian to lower Carboniferous periods generally gave rise to the formation of quartzite, purple sandstone, shale, salt and minor quantities of gypsum.

Study of Palaeozoic formations, all over the world, establishes clearly that while the Gondwanaland was rising slowly making the inland seas shallower, taking the form from marine to fluviatile characteristics, the land mass situated north of Tethys sea was submerged, to a large extent, under the inland sea throughout the Palaeozoic era.

Land masses of northern continent was affected by Caledonian orogeny during Silurian period. At the end of succeeding Devonian period there were two regions of contrasted facies of depositions in Europe. One region with a tropical climate constituting the Scandinavian, Baltic, and British in which the red sandstone was developed, and the other was Mediterranean geosyncline which deposited mainly shale. The red sandstone became land area covered with extensive lakes and shallow seas in which limestone and dolomite was developed. European regions, including North America, the USSR and China by the close of Devonian, had become a vast continental area in which swamp and brackish water deposits like shale and minor coal seams were formed. Towards the upper Carboniferous, some 300 million years ago from the present, a most significant global change took place on the earth's surface heralding a new era in geological history termed as 'Gondwana' Age which gifted us vast coal deposits. It lasted for about 150 million years up to lower Cretaceous, depositing some 9,000 metres thick sediments of sandstone, shale and coal. All the major coal deposits in the world belong to this group particularly of Permian period and to smaller extent from Triassic, Jurassic and Cretaceous in some part.

The Gondwana group in the southern continent began with melting of thick ice sheets, then covering a large part of the Gondwanaland, for we find in all the continents forming the Gondwanaland, the deposits of this group began with glacial deposits like tillites (moraines) containing boulders of Archaeans and other pre-Cambrian formation. In this part of the continent, deposition took place in fresh water lakes and basins. On the other hand, the northern continental mass began with different environment beginning with marine facies, unconformably overlying red sandstone or magnesium limestone.

On the whole, it can be concluded that Permian was a period of luxuriant growth of forest trees quite tall and thick and of torrential rains which washed, deposited and buried the forest trees which later became coal. Although there is difference in facies of deposition in southern and northern continents, the former beginning with glacial deposits and the latter with marine deposition, there is remarkable similarity in the cycle of deposition in both regions each starting from sandstone and proceeding through shale and coal. Facies denote the total characters of a rock—its composition, texture, structure, fossil contents and all its other qualities. There were several cycles of deposition in Permian, Triassic and Jurassic periods, each cycle giving rise to a coal deposit, some depositing over 30 metres thick seams. Kargali seam of Bokaro coal field in Bihar, and Jatraj coal seam of Korba, Madhya Pradesh, upper seam of Talchir coal field, Orissa, Purewa seam of Singrauli in Madhya Pradesh and Uttar Pradesh measure more than 30 metres in thickness. In India, at least 50-60 cycles are noted, all in Permian period. Gondwana is known as Karoo system in Africa, Santa-Catarina system in South America and with different names like Mississipian and Pennsylvanian in United States and with other names elsewhere. Coal beds of this system belonging to Permian period are well developed with varying thickness in Orissa, West Bengal, Bihar, and Madhya Pradesh in India; Queensland, New South Wales and Tasmania in Australia; Cape and Transvaal, Republic of South Africa; Zimbabwe, Zambia, Tanzania, Botswana in Africa; Brazil and Argentina in South America, in vast area covering the USA, Canada, the UK; Saar, Ruhr in Germany; Donetz coal basins of the USSR, Silesia, Belgium, France and several parts in Europe and areas adjoining eastern part of Russia and southern part of China. Coal deposits belonging to Triassic and Jurassic periods are also found in Europe and elsewhere. In Queensland there are about 22 workable Triassic coal seams. In China, Japan, Alaska (USA), Canada, Germany, Siberia in the USSR and North and South Vietnam, Cambodia, Laos and South Korea, North Korea, Australia, New Zealand, there are coal deposits which date from Jurassic to Cretaceous. In nutshell, the period starting from lower Carboniferous up to Jurassic was most dominant for coal formations.

It is notable that the Hercynian movement during Permian time had brought a stratigraphical break in the coal formations in the northern continent. In the areas affected by this movement we find coal seams folded, with other structural disturbances. In other areas of the northern continent and all over the southern continent where Hercynian movement did not affect, the coal seams are more or less horizontal, with minor faults and unconformities marked by conglomerate bed maintaining the same original modes of deposition in the way they were laid.

Hercynian movement had marked the close of the Palaeozoic era. As said earlier the major part of the Mesozoic era comprising Jurassic, Triassic and lower Cretaceous laid down Gond- wana sediments in troughs and basins which were receptive to such formations; the Mesozoic era otherwise also was very important which can be regarded an era of great erosion, marine transgression and regression, igneous intrusions and volcanic activities. Mesozoic formations are best developed throughout Europe. The best studied area is the Jura mountain range of France where a complete succession of Mesozoic formations from littoral to marine facies are found. Mesozoic formations are very important for north Europe and the UK for giving rise to world famous chalk deposits of highest purity resulting from the decay of marine organism coccolith.

Triassic was generally a dry period. The Hercynian mountain ranges were subjected to erosion and brought to near peneplaination. The best developed formation of Triassic period are known as Germanic facies, because it was first studied in Germany, containing three formations resting uncon- formably on the new red sandstone of Permian. The names of the three formations are: (*i*) Buntsandstein; (*ii*) Muschelkalk; and (*iii*) Keupar. The Buntsandstein facies gave rise to sand- stone, conglomerates and shales deposited in lagoons, with red to white colours. The upper series of this formation practically contain a bank of shell facies like Lingula, Myophoria etc. The succeeding formation namely Muschelkalk consists about 400 metres of shelly limestone. The Keupar formation is generally marly with calcareous shale. At a number of places in Europe and North America, the shallow basins gave rise to deposition of gypsum and anhydrite. A great volcanic activity was also witnessed during the same period in the eastern part of USA and Canada, North Africa, West Africa and South Africa, and in Australia depositing basaltic lava measuring some 2,000 metres thick. When the eastern part of the USA was witnessing volcanic activities, the western part of it was inundated by sea from Arctic region covering Utah, Idaho, California, South Dakota and Rockies. Gypsum beds of USA are mainly of these facies. By the end of Triassic, the continent of Hercynian chain was almost completely transformed into huge deserts. But during Jurassic, again two periods of marine transgressions and regressions are observed from Arctic sea covering large part of Europe and Russia giving rise to formations of limestone and marls. Jurassic formations are well developed in Crimea, Caucasus in Russia and many parts of Europe. There appears to be no marine inundation in China after Permian period except in a small area in coastal region of Ussuri where the Arctic sea had invaded during Jurassic. The Jurassic and Cretaceous formations in China are found of fresh water origin. On the other hand, Jurassic and Cretaceous formations of Tibet are entirely of marine. There seems to be little geological activities during Triassic in the Gondwanaland. In the Jurassic period a significant event took place. Western India which had not witnessed any deposition after Vindhyan was flooded by an arm of Tethys sea covering whole of Western Rajasthan and Gujarat giving rise to rich deposits of limestone, gypsum, phosphorite and fireclay. The Jurassic rocks in Kutch attain great thickness of about 7,500 metres at some places, which indicate the magnitude of deposition during Jurassic flood. This part of the country remained partly under the sea till Tertiary era. In Cretaceous period a remarkable universal marine invasion took place in different parts of the continents. This marine flooding is commonly known as Cenomanian transgression which approximately occurred in the middle of Cretaceous. As a result of this, sea invaded a large area of the Coromandal coast from near Pondicherry to the Cauvery valley. Beautiful exposures of Cretaceous rocks are exposed in Tiruchirapally where the deposits have been divided into four stages from below to top, namely, Uttattur, Trichinopoly, Ariyalur, and Niniyur. These formations lie on the ancient rocks. The Cretaceous succession consists mainly of limestone, sandstone and shale. The formations of Uttattur and Trichinopoly stages are a good source of gypsum in South India. An arm of Tethys sea is found to make an incursion into Narmada valley as well. A large area of Tibet, Northern Himalaya, Burma, Arakan range, Assam are covered by rocks of this period. During the same Cenomanian transgression, the Mediterranean sea advanced northward through Mexico and mixed with Arctic sea. Subsidence kept pace with deposition until sediments measuring over 9,000 metres were laid in the central trough. Cretaceous beds are exposed in a broad belt of about 160 km wide in Western Canada and Alaska. The Cretaceous formation of North

America and Venezuela, in addition to formations belonging to Ordovician and Permian, are the rich sources of petroleum.

The northern part of Africa which was then occupied by Mediterranean geosyncline, widened, over-flooded and sea water moved south up to the heart of Africa. We, therefore, find the whole northern part of Saharan continent containing Cretaceous and Tertiary sediments, now covered under the sandy beaches, resting on ancient rocks. The marine transgression also took place in Australia, largely in East coast and to a small extent in the West coast. There was a world-wide regression of sea towards the close of Cretaceous exposing the vast continent masses like today. The retreating sea lavishly gifted vast deposits of useful minerals like gypsum, salt, coal, petroleum and chalk. During the same period, the Indian sub-continent broke loose from Africa and started moving towards north. This was accompanied by stupendous volcanic eruptions which continued intermittently lasting up to Eocene. The basaltic lava flows commonly known as 'trap rock' extensively occupying the vast area of Maharashtra, Madhya Pradesh, Gujarat in India, East and South Africa, Brazil and China are the results of volcanic activities during the last phase of Mesozoic era. This was a period of orogenic movement, which is known in geological history as Laramide orogeny. For China, Cretaceous period is singularly important because this part of the land mass of Asia witnessed extensive and intensive igneous eruptions and intrusions giving rise to several useful metallic mineral deposits. In China, therefore, Cretaceous period is characterised as a metallogenic epoch.

Igneous activities both extrusive and intrusive during Cretaceous period were quite extensive and world-wide. The Rajmahal lava flows of Bihar and extensive dyke intrusions in the coal fields of India belong to Deccan trap age. Beds of basalt, peridotite and serpentinous rocks of Baluchistan and India are of this age, which are the source of chromite and asbestos. Basic rocks of same age cover widespread area of Andaman and Nicobar islands specially in Central region.

The first breaking of Gondwanaland and consequent widespread volcanic activities marked the end of the Mesozoic era. The Tertiary era which followed emerged with entirely new environment, as we find widespread extinction of giant reptiles, ammonites, flying birds and evolution of new flora and fauna.

This era was again a period of multiple marine transgression, regression, igneous activities and lifting up of the great Alpine-Himalayan mountain range. The Kimberlite eruptions in African continent providing a universal source of diamonds are regarded to be of late Cretaceous or early Tertiary period.

It has been described earlier that by the close of the Cretaceous period, the Indian sub-continent broke loose and started moving towards the north. This was the beginning of the first orogenic movement brought in the Tethian area. The evidence of the first compression is recorded in the Mediterranean region during late Cretaceous and early Eocene period thus exposing a vast sediment of late Cretaceous and early Eocene throughout the northern part of the African continent and the Middle-East countries depositing a vast amount of phosphorites, a source of phosphorus. Mediterranean region which was raised as a land mass during early Eocene was again subjected to marine transgression during Miocene for a brief period. As discussed in chapter 5, the entire Alpine-Himalayan basin was subjected to four major orogenic movements during upper-Cretaceous, upper-Eocene, middle Miocene, and close of Pliocene. During each orogenic movement, the basin was shallowed and raised above which was again subjected to erosion and deposition. We find widespread different formations of upper-Eocene throughout the Himalayan belt from West to East commonly known in Indian stratigraphy as Nari, Gaj and Murree strata having marine to brackish water characteristics. The most powerful orogenic movement during the middle Miocene completely shallowed the Tethys sea which was replaced by the mountain ranges. The same force created a trough between Peninsular India and the Himalayan range commonly known as a 'foredeep' which is now filled with sediments grouped as 'Siwalik'. Such foredeep is found in the entire Alpine-Himalayan range.

Siwalik is called Manchar in Sind and Irrawaddy in Burma. The uplift of Himalayan range overflowed the Tethys sea water both towards North and South covering a wide area in Assam and Burma. The Tertiary formations of varied thickness are found all along the foothills of Alpine-Himalayan range. In the Western part of India the Tethys sea which had invaded during Jurassic period continued deposition of sediments during Tertiary. Such Tertiary formations are well located in Gujarat

TABLE 7.2. SUCCESSION OF TERTIARY FORMATIONS IN ASSAM AND MEGHALAYA

Age	*Central and lower Assam*		*Upper Assam*
Pliocene	Dihing series (3000 m)	Pebble bed, bands of clay	Dihing series
		Unconformity	
Mio-Pliocene	Dupi Tila series (3000 m)	Sand and clay	Namsang stage
		Unconformity	
Miocene to upper Oligocene	Tipam series (3900 m)	Girujan clay—with sandstone, Tipam sandstone with minor clay (Petroliferous)	Girujan clay Tipam sandstone
	Surma series (6000 m) (this thickness is attained toward Arakan region)	Boka Bil stage—sandy shale and sandstone (1500 m) Bhuban stage—sandstone, conglomerate and shales (2400 m)	Surma series
		Unconformity	
Oligocene	Barail series (5700 m)	Ranji stage—hard massive (900 m) sandstone (Petroliferous)	Tikak Parbat stage (450 m) carbonaceous shale and coal seams
		Jenam stage—sandstones (Petroliferous) (1200 m) and carbonaceous shales	Baragoloi stage—sandstone (3000 m) carbonaceous shale and coal seam
		Laisong stage—sandstone with (2400 m) minor shale (Petroliferous)	Naogaon stage—(2400 m) limestone and sandstone
Eocene	Jaintia series (1200 m)	Kopili stage—mostly carbonaceous shales Sylhet stage—nummulitic limestone Therria stage—sandstone and limestone	Disang series (3000 m)
		Unconformity	
		UPPER CRETACEOUS Trap rocks	

up to the Gulf of Cambay and towards West up to Kutch and in Rajasthan. Evidences of marine transgression are found over coastal tracts of Orissa, Tamil Nadu and Kerala.

The Tertiary sediments are very significant for the formation of petroleum; gypsum, sulphur, salt and lignite. It is now well established that the foraminifera which took birth and grew luxuriantly during this era are the main agency in the formation of hydrocarbons. Lignite and also bituminous coal seams are extensively mined which belong to Tertiary era. In Assam, there are several coal seams of Tertiary age. The marine transgression of lesser magnitude which took place in Eastern part of Peninsula covering Pondichery gave rise to lignite coal seam known as Neyveli lignite. The oil fields of Assam and Gujarat belong to Tertiary. Deposits of this era, besides being the source of oil and lignite, have given rise to nummulitic limestone deposits in Rajasthan and Gujarat which are extensively mined and marketed as chalk. Sandstone deposits are used for making beautiful carving and decorative windows. In Victoria, Australia, the Yallournian lignite measures of Gippland are one of the most remarkable brown coal deposits in the world. During this era several geosynclinal basins of a small magnitude in comparison to Tethys *viz*. Tasmania geosyncline, Australian geosyncline and Papuan geosyncline were compressed and raised into mountain ranges. In Mediterranean region, sandstone, calcareous shaly sediments of Tertiary are widespread. In Europe, the type area of Tertiary sediments are Bordeaux and Vienna basins where mostly marine molasses (unconsolidated sandy sediments) are found. Coastal regions of Louisiana and Texas in USA and Mexico and the Central and Western part of Canada are the rich source of petroleum from Tertiary horizons.

The succeeding Pleistocene era commenced with lowering of temperature which brought widespread advent of glaciation. This era as well as the Recent have not provided formation of much economic significance. During this period mainly unconsolidated sediments, clay, silts and sand have been deposited. The close of Pleistocene was marked by temperate climate which resulted into widespread lateritisation. Bauxite deposits found in various parts of the world, in tropical region, are regarded to be of post-Pleistocene age.

8

The Rocks of the Surface

In the preceding chapter the events leading to the formation of different rocks and rock-beds on the earth surface from Archaean to Recent have been described. The original source of all rocks is magma. Magma is the geological term for the molten mass of the crust, which on consolidation gives rise to rocks. As a matter of fact, the original rocks formed by the consolidation of the magma are nowhere to be seen, as these have undergone complete transformation, and now overlaid by rocks of subsequent periods. We may recapitulate that there were several moments in the earth's history when the molten magma was forced up to the surface, and later, this after consolidation was subject to large scale erosion by weathering actions leading to the formation of layered beds or strata. The entire earth surface, therefore, constitutes of a variety of rocks and beds formed as a result of geological processes, covered with a thin mantle of soil, at places attaining great thickness. The soil is the result of weathering of the rocks—providing vegetation, which is essential for life.

It should be clear now that if we chemically analyse the various rocks and soils, these will indicate the presence of mainly eight elements, namely oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium (as we have already read in chapter 2) in various proportions, chiefly as oxides and silicates. The elements, by and large, do not occur in free state but are found in combination with one another depending upon their chemical affinity. Two or more elements combine to form one stable mineral. There is some exception to it which we shall discuss in the next chapter. Two or more minerals combine to form a rock although few rocks consisting of single minerals, such as quartzite, sandstone, limestone are also known.

Rocks are placed under three distinct groups, namely, igneous, sedimentary and metamorphic, depending upon their modes of formation. All rocks formed from the cooling and consequent solidification of the magma are called igneous or primary. The igneous include both extrusive and intrusive rocks. Volcanic (extrusive) rocks are formed from the cooling of magma which has ejected out of the surface. Intrusive rocks result from the magma of non-volcanic character, which has solidified before reaching to the surface. Sedimentary rocks are formed by disintegration of the pre-existing rocks, which are carried either in solid particles as sediments or in solution and get deposited elsewhere as layered beds. The pre-existing rocks may be igneous, metamorphic and the earlier deposited sedimentary rock itself. Sedimentary rocks are sub-divided into three classes, namely, mechanical, chemical and organic depending upon the process of origin. Sedimentary deposits are also called 'secondary' because they are composed of second hand derived material. The rocks either igneous or sedimentary which have undergone intense heat and pressure, leading them to recrystallise and readjust the previous mineral structure often forming new minerals by such orientations, are called metamorphic rocks or metamorphosed sediments. A metamorphic rock might have undergone finally several cycles of heat and pressure.

IGNEOUS ROCKS

We have just read that the igneous rocks are both extrusive and intrusive. Since they are formed by the consolidation of magma, they have some texture. A texture, is referred to grain size (crystallinity) of minerals and their interlocking in a rock, as observed under microscope. In other words, it can be said to be a fabric of minerals in a rock. The meaning of texture should not be confused with the structure which is a visual appearance of a rock. Texture is the most distinguishing characteristics of all igneous rocks. It depends largely upon the environment of consolidation *i.e.* on the rapidity with which the magma has cooled. The magma which erupts out, cools rapidly allowing little time for atoms to arrange themselves into crystals and in that case the rocks attain fine grained texture. Faster rates of cooling impart densely fine grained and glassy textures.

All volcanic rocks have fine to glassy texture. Intrusive magma, on the other hand, cools slowly allowing enough time for crystals to take shape, thus giving rise to coarse texture. Deep seated intrusive rocks, also called plutonic, show euhedral crystals visible even by naked eyes. Two other types of texture are commonly referred to, the first, even grained in which crystals are more or less of the same size and the second, porphyritic in which large crystals are found enclosed in the ground mass. Porphyritic texture is a result of cooling followed by rapid cooling. Large crystals of felspar enclosing imperfectly developed quartz is known as graphic texture.

Variety and Basis of Classification

It is obvious that a particular variety of rock going to be formed will depend upon the chemical and mineralogical constituents of the magma and its intrusive or extrusive character. The most abundant elements, oxygen and silicon of the magma readily combine to form silica (SiO_2). Oxygen and silica may combine with other elements to form oxides and silicates. The magma over-saturated with silica give rise to formation of mineral quartz and other minerals rich in silica. Silica and silicates are thus symbolic minerals of rock constituents. Depending upon the richness in silica, the magma may give rise to a rock containing minerals requiring high, medium or low silicification. A student of mineralogy will understand better that the most silica rich rock forming minerals belong to felspar group. Orthoclase, $K_2O.Al_2O_3.6SiO_2$, is commonest mineral of felspar. The silica percentage in this mineral is about 65 per cent. Potassium of orthoclase may be replaced by sodium to form another mineral of the same group, namely, albite ($Na_2O.Al_2O_3.6SiO_2$). A less silica rich felspar containing 43.2 per cent SiO_2 is anorthite, $CaO.Al_2O_3.2SiO_2$. It invariably forms an isomorphous mixture with albite, referred to as plagioclase series, wherein five minerals, namely, albite, oligoclase, andesine, labradorite, bytownite and anorthite are identified, showing decreasing silica percentage from albite to anorthite. It is found that an igneous rock containing orthoclase or albite is always associated with free quartz. On the other hand, presence of calcium rich plagioclase make the rock relatively devoid of free silica. Other unsaturated silicate minerals of alkalies, are that of felspathoid group represented by nepheline, $NaAlSiO_4$ and leucite $KAlSiO_4$. Felspathoid group of minerals are formed where the magma becomes poorer in silica and richer in alkalies and alumina. A magma of basic character, in other words, rich in calcium, magnesium and iron, forms minerals of low silicification. They are grouped under pyroxene, amphibole and olivine, commonly known as *mafic* minerals. Pyroxene is represented by a type mineral augite, amphibole by hornblende, both being a complex silicate of calcium, magnesium, iron and aluminium. Olivine is represented by type mineral olivine, $(Mg, Fe)\ SiO_4$. The minerals of above listed five groups (felspar, felspathoid, pyroxene, amphibole and olivine) constitute rocks forming minerals. These groups are representative of minerals of high to low silicification. The presence of total silica which also reflects the likely nature of mineralogical composition, therefore, forms the basis in classification of igneous rocks. The magma rich in silica is called acidic and that low in silica basic. On the basis of total silica, igneous rocks are classified into acid, intermediate, basic and ultrabasic. An acid rock contains over 66 per cent of SiO_2; intermediate between 66 to 52 per cent of SiO_2; basic between 52 to 45 per cent of SiO_2 and ultrabasic below 45 per cent of SiO_2. Hundreds of rocks analysed so far have shown silica percentage varying from a little over 72 per cent to as low as 42 per cent in ultrabasic rocks. Geologists have listed over hundreds of igneous rocks, but only about a dozen can be said to be most representatives by way of their distribution and importance. Others are names of the same dozen varieties depending upon a little variations in some specific mineral constituents.

TABLE 8.1. NAMES OF COMMON IGNEOUS ROCKS

Type	*Volcanic*	*Intrusive or Plutonic*
Acid	Rhyolite Dacite	Granite Granodiorite
Intermediate	Trachyte Andesite	Syenite Diorite
Basic	Basalt	Gabbro
Ultrabasic	Olivine-rich Basalt	Peridotite and Dunite.

TABLE 8.2. TEXTURE OF COMMON IGNEOUS ROCKS WITH MINERALOGICAL COMPOSITION

Rocks	*Texture*	*Mineralogical composition*
1. Rhyolite	Fine grained	Quartz + orthoclase felspar primary (nearly 40% free quartz)
2. Granite	Coarse grained even texture	Same as above
3. Dacite	Fine grained	Quartz (about 15%)+alkali felspar dominant, soda plagioclase
4. Granodiorite	Porphyritic	Same as above
5. Trachyte	Fine grained	Soda plagioclase + hornblende, no quartz
6. Syenite	Medium to coarse grained, even texture	Same as above
7. Andesite	Fine grained	Intermediate plagioclase + hornblende, minor pyroxene
8. Diorite	Medium to coarse grained, even texture	Same as above
9. Basalt	Fine grained	Calcic-plagioclase+ augite hornblende+olivine
10. Gabbro	Medium to coarse grained, even texture	Same as above
11. Olivine rich Basalt	Fine grained	Calcic-plagioclase + olivine predominant+pyroxene
12. Periodotite	Medium to coarse grained	Olivine predominant + pyroxene
13. Dunite	Coarse grained	Chiefly olivine

On the surface, however, basalt and granite are most predominant and widespread. Eruptive type acid igneous magma forming rhyolite and dacite are less common because silica rich magma being viscous does not generally come up as volcanic mass. It is not very difficult for an experienced geologist to identify these most common rock types by visual inspection. By and large different rock types are identified by examining their thin sections under petrological microscope.

The most common lava is basalt. Under microscope, it is found to contain 46 per cent of felspar, 37 per cent augite, 7.6 per cent olivine and minor quantities of accessory minerals like magnetite, ilmenite etc. Basaltic lava has more fluidity and is found to cover wide area. Hence it is commonly called trap rock. Deccan trap is a familiar name to every one in the country. It covers extensively stretching far and wide areas practically three-fourth of Maharashtra and some portions of Madhya Pradesh and Gujarat. Basaltic magma sometimes give cavity like structures due to disengagement of volatile matters during the course of solidification. It is then known as amygdaloidal. Cavities later get filled with secondary minerals like zeolite, calcite and chalcedony. Pillow shaped masses are formed when lava flows down in the ocean. A portion of basaltic magma when fails to reach the surface and solidifies as intrusive bodies in the form of dykes and sills is known as dolerite. They are also of fine grained, characterised by ophitic texture where laths of plagioclase felspar are found enclosed in augite as observed under microscope. Dyke occurs like a vertical wall, standing erect cutting through the earlier rocks. Many such dolenite dykes are seen in Singhbhum district, in Jharia coal field and elsewhere. Sills form intrusive mass nearly parallel to bedding planes. Basaltic lava is still being poured out intermittently, as is evident from several active volcanoes in the Pacific and Indian oceans. Several small islands in the Pacific and Indian oceans are formed entirely of basalt. If one visits Mauritius, he will observe a volcano emitting lava continuously at nearby ReUnion island situated about 100 km north-west of Mauritius.

Granite which is another widely occurring rock type can be easily distinguished megascopically *i.e.* by visual examination. It consists chiefly of quartz and orthoclase interlocked to each other. Granite containing appreciable amount of soda-plagioclase is known as quartzmonzonite; and in which soda-plagioclase exceeds orthoclase is known as granodiorite. Granites usually contain accessory minerals like mica, magnetite, apatite, zircon, cassiterite and several other useful minerals.

An accessory mineral is one of which presence or absence does not make any difference in the nomenclature of a rock type. Accessory minerals, although occur in small quantities, often become a powerful source of by-product minerals and metals during ore-dressing and metallurgy. Granite magma consolidating as dykes and sills is known as aplite, contemporary to dolerite of basic magma. The mode of occurrence of aplite and dolerite is recognised to be hypabyssal, half-way between plutonic and eruptive. Volcanic equivalent to granite and granodiorite are rhyolite and dacite which form glassy rocks due to quick chilling. Glassy rocks are known by different names such as obsidian, pitchstone, according to appearance. If the entire rock is composed of glass having bright and vitreous lustre it is called obsidian; pitchstone when its lustre is dull and pitchy. Pitchstone is often found to contain combined water ranging between 5 and 10 per cent. Obsidian often contains water molecule but not exceeding 2 per cent. Volcanic dust or ash when they accumulate after being blown out, form pyroclastic rocks. Pumice and pumicite are the names given for pyroclasts of acid rocks. In trade, the material containing grain size more than 2 mm is called pumice and those containing smaller size down to powder termed as pumicite. Pumice is light in colour, highly vesicular giving rise to cellular structure which is formed by rapid cooling and expulsion of gas, chiefly water vapour. It does not normally contain water molecules. In appearance it looks like frothy material. Because of the cellular structure the apparent density of pumice is less than 1. It floats on water for a long time. Pumice and pumicite are used as an abrasive for finishing wooden work, polishing metal parts which are required to be electroplated, as a filter aid and loose fill insulation. It forms an important ingredient in the manufacture of hard soaps. Volcanic rocks of rhyolitic composition containing 2-5 per cent combined water is termed perlite and characterised by concentric and spheroidal cracks, referred to as perlitic structure. Perlites possess ability to expand like popcorn 20 times its original volume on rapid heating to its softening point. The expanded material has snow-white to light grey-white appearance. The treated product is known as expanded perlite and largely used as light weight gypsum-perlite plaster and wall board. It has been found to be a good substitute of diatoms in filter aid. The most distinguishing characteristic between obsidian, pitchstone, pumice and perlite, besides colour, is the expansion property determined by the proportion of combined water. Amongst glassy rocks, perlite pops most and finds extensive use in the expanded form. Commercial deposit of perlite or pumice is not known in India. Tuff is the common name for volcanic ash or dust.

A magma containing right proportion of lime, alkalies and silica may consolidate as anorthosite rock constituting wholly of felspar group of minerals chiefly of lime-soda plagioclase. A rock containing predominantly olivine with pyroxene is known as peridotite and that containing chiefly of olivine as dunite. These ultrabasic rocks are regarded to be formed due to gravity separation of earlier formed minerals from the magma and later pushed up a plutonic mass. Ultrabasic rocks do not occur as volcanic rock. Ultrabasic usually contain chromite, spinel and nickel minerals as accessories.

SEDIMENTARY ROCKS

Sedimentary groups of rocks occupy an important place amongst the rocks on surface, covering about 75 per cent of the total land area. Minerals in sedimentary rocks, as mentioned earlier, belong to three distinct categories, *viz.* mechanical, chemical and organic. In the former process, the mineral grains of weathered rocks carried away mechanically by running water like rain and river either in suspension or as rolling, bumping and sliding and get deposited in low lying basins and seas, forming sedimentary beds. Alumino-silicate minerals easily get disintegrated into finely clayey material and flow in fine suspension. More resistant minerals like quartz, quartzite, chert or some portion of rock itself which do not get easily abrased, roll and slide with the flow of the current and these get progressively sorted and deposited in order of densities much earlier than the fine material, synchronising with velocity of current. An understanding of the sedimentary beds involves determination of the source rock and the source area from which the sediments came and the mechanism of transportation and maturity attained. In chemical or mineralogical composition, therefore, the sedimentary rocks of mechanical origin correspond more or less to the source rocks, except to the extent to which the original mineral grains have gone into solution. Lithification of sediments, in stratified fashion, layer after layer at relatively low temperature and pressure leads to the formation of sedimentary rocks. Lithification is a process that converts a newly deposited sediment into compact rock by combined process of pressure, heat and cementing action. In this process each layer of sediments is buried more as succeeding layers are deposited on top of it. The action of pressure or heat in the process of lithification, consequential to weight of overlying deposition and gradual sinking of underlying sediments is not to be mistaken to a process of metamorphism. Heat or pressure acting in this manner is excluded from the activities of metamorphism. Huge accumulation of such sediments are found measuring several thousand metres thick. Gondwana and Tertiary basins are the classical examples of sedimentary deposits.

Clay, silt, sand, gravel, shale, siltstone, sandstone, conglomerate and air-borne desert sand are the most common sediments and rocks formed by the mechanical process. In such beds, mineral particles are found more or less rounded to sub-rounded in shape, owing to the abrasion they suffer during the course of transportation. Depending upon the particle size and shape, the sediments and the rocks formed thereof are classified as in Table 8.3.

Table 8.3 shows, how sedimentary rocks are classified according to size of the material. Conglomerate bed consists of rounded rock material cemented together. The rock fragments get polished and rounded during the course of transport. Breccia is the name given for bed containing angular material indicative of the fact that the loosened fragments of rocks have travelled no distance. Breccia usually result near the fault zone, and often called fault-breccia. Talus or scree is the name given for loosened rock material found on the slope and at the bottom of the hill. Talus is called 'float' when it consists chiefly of some ore and economic material. Agglomerate is the breccia containing volcanic fragments.

Mechanical process is an important means of forming mineral deposits by gravity concentration, as for example, placer depo-

TABLE 8.3. CLASSIFICATION OF SEDIMENTARY ROCKS BASED ON SIZE OF THE MINERAL PARTICLES

Major group	*Sediment*	*Diameter of particle size in mm*	*Rock (formed after cementation and lithification)*
Gravel	Boulder	More than 256	Conglomerate
	Cobble	Between 256—64	,,
	Pebble	,, 64—4	,,
	Granule	,, 4—2	,,
Sand	Very coarse	2—1	Sandstone
	Coarse	1—.5	,,
	Medium	.5—.25	,,
	Fine	.25—.125	,,
	Very fine	.125—.062	,,
Silt	Silt	.062—.005	Siltstone
Clay		Less than .005	Shale

sits of diamond, gold and tin ore; ilmenite, rutile, sillimanite, garnet and monazite as beach sands and iron, manganese and tungsten ores as float ores.

Chemical process is also very important in the formation of monomineralic rock beds of high purity. Most of the minerals go into solution in flowing water under different acidic and alkaline conditions and thus go on accumulating in sea and basin, and later get precipitated by inorganic processes, under specific condition. Important mineral deposits formed by this process are limestone, dolomite, pyrites and those grouped under evaporites such as gypsum, common salt, nitrates and borax. By combination of mechanical and chemical processes, mineral deposits like bauxite and china clay are formed. In organic process, the natural property of some sea habitats both animal and plant in making, secreting and more often their skeleton or tests forming mineral matter like calcite, chert, give rise to valuable mineral deposits like chalk (friable limestone), coral limestone, chert, diatomite and phosphorites in addition to petroleum. Formation of iron ore and quartzite is also now regarded as formed by the action of aquatic algae and fungi and can be placed under organic origin. The formation of mineral deposits by sedimentary process deserve special attention. It has been described in greater detail in chapter 9.

As it is evident now, sedimentary rocks differ genetically from igneous rocks. They inherit altogether different texture and are characterised by bedding planes, unconformity, contamination of detrital material and fossil contents. Unlike igneous rock, where mineral grains are interlocked with each other in a particular fashion giving rise to a particular texture chracteristic of a rock type; in the case of sedimentary rocks the mineral grains are found cemented to each other giving rise to characteristic clastic (detrital) texture. The texture of sedimentary rock is further defined upon the shape and size of the mineral grains and the extent to which it has matured *i.e.* lithified. Medium to coarse grained sandstone make first class acquiferous bed and reservoir for petroleum. Finely layered beds of silt and shale are impervious and serve as a blanket in preventing migration or seepage of petroleum and water.

METAMORPHIC ROCKS

Metamorphic, as the name implies, means change of form. Metamorphic rocks are those which have undergone physical or chemical change subsequent to their original formation due to intense heat, pressure or by chemically active fluids. Magmatic solutions, vapours and gases are generally known as chemically active fluids or magmatic fluids. Rise in heat, pressure and action of chemically active fluids result from the igneous activities usually associated with crustal movements. The process of physical or chemical transformations in a pre-existing rock by actions of heat, pressure and magmatic fluids is known as metamorphism. Igneous and sedimentary rocks are susceptible to metamorphism. The mineral constituents of these rocks respond to heat and pressure and try to readjust and rearrange themselves forming new and more stable minerals suited to changed conditions. A new equilibrium in the composition of a rock is thus attained. Combined actions of heat and pressure provide optimum condition for more or less complete recrystallisation of mineral constituents, and development of new fabric. Directed pressure or stress greatly influences the fabric of a metamorphic rock. Stress causes shearing movement and gives rise to formation of new minerals of platy habit. Under the influence of stress, minerals arrange themselves approximately parallel to stress. This parallelism in texture is known as schistosity; and the banding produced in the schistose material is known as foliation. A metamorphic rock may undergo several cycles of metamorphism, each time making new adjustments in the mineral constituents and the texture until final stability has been achieved. Typical examples of poly-metamorphism are exhibited by the rocks of Archaeans and Dharwars.

The banded or foliated character given by the parallelism of minerals is a striking character of a metamorphic rock by which property it is generally distinguished from igneous and sedimentary rocks. In most of the cases, a metamorphosed sedimentary bed attains partial to complete crystalline structure which distinguishes it from original sedimentary bed. For example, a bed of limestone or dolomite may change to marble; shale and tillite into phyllite, slate to mica schist depending upon the intensity of heat and pressure. The most common igneous rock granite changes to gneiss showing banded structure. A sandstone under intense heat and pressure changes into quartzite. Chemically active fluids, emanating from intrusive magma, and percolating through the intragranular network of a rock, play an important role in bringing significant changes in the composition of a rock by addition or removal of some constituents. This phenomenon is known as metasomatism which is an important process in the formation of many useful minerals under the realm of metamorphism.

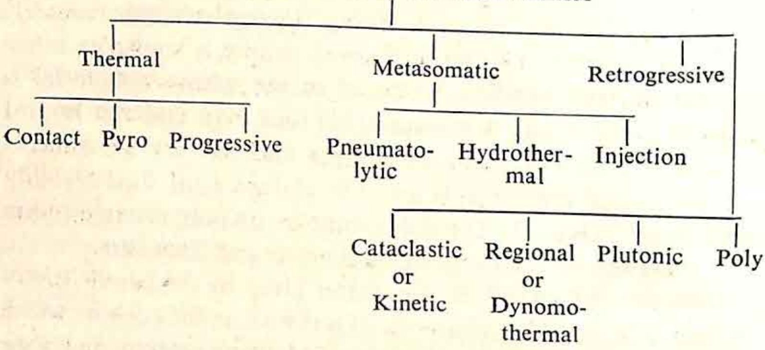
An important point of metamorphism which deserves mention here is that certain minerals which are of igneous origin can also be formed by metamorphic processes. Most of the igneous minerals do exist in metamorphic rocks but there are a large number of minerals which are peculiar to metamorphics only.

Types of Metamorphism

Different types of metamorphism have been recognised in the field, depending upon the degree of heat and the extent to which magmatic fluids have played their role. These are schematically detailed in Table 8.4.

Thermal metamorphism includes all types of transformation in which heat is the dominant factor. It is divided into three

TABLE 8.4. TYPES OF METAMORPHISM



classes—contact, pyro and progressive. Thermal metamorphism takes place in the proximity of igneous intrusive masses. It is called contact metamorphism when the temperature of intrusive mass varies between 500°C and 1000°C. Pyrometamorphism includes intense local changes at very high temperature usually above 1000°C. It takes place at the immediate contact of igneous plutons with the country rock. A metamorphism is termed progressive when the degree of metamorphism changes progressively from high to low intensity.

Metamorphism involving substantial addition and removal of material such as in kaolinisation, sericitisation, steatisation and serpentinisation is termed as metasomatic metamorphism. Addition of material is chiefly brought by silicon, tin, lithium, chlorine, fluorine, boron and sulphur. Pneumatolytic metamorphism is called to an action where the introduction and removal of material take place through mineralised gases; and where the magmatic acqueous solution and vapour are the medium of introduction and removal, it is termed as hydrothermal. Hydrothermal metamorphism is localised to fractures and fissures in rocks. Distinction between chemical process of sedimentary origin and that of metasomatism should be clearly understood. The chemical action under the sedimentary process takes place through the medium of ground water, surface water or atmospheric water, whereas in the case of metasomatism it is the magmatic vapour and acqueous solution which come into play in bringing out changes in the rock structure at depth. As said before, magmatic intrusions are the source of chemically active fluids. In general, the greater the size of intrusive mass the greater will be the effect of heat and metasomatism. As a rule granite magmas are richly charged with chemically active fluids than gabbroic magmas, and therefore, metasomatic actions are more pronounced near granitic intrusions.

Injection metamorphism is the name given to where addition is through liquid quartz-felspathic material. A rock which has suffered from injection metamorphism develops migmatitic (mixed) structure. A large scale injection metamorphism may convert gabbroic rocks into granitic mass.

Retrogressive is a term used where high temperature metamorphism respond to low temperature metamorphism. High metamorphic rocks like granulite, eclogite, and charnockite are particularly susceptible to retrogressive metamorphism in the presence of pore-fluids at low temperature. Even reversible action also takes place with the increase of pressure, *e.g.*

$CaCO_3 + SiO_2 \rightarrow \underset{\text{(Wollastonite)}}{CaSiO_3} + CO_2$ With increase in temperature

$\underset{\text{(Wollastonite)}}{CaSiO_3} + CO_2 \rightarrow CaCO_3 + SiO_2$ With increase in pressure.

Cataclastic metamorphism happens due to the dominant action of powerful shearing stress. It takes place in orogenic belts. The powerful tangentially directed pressure is manifested by low angle faults and overthrusts, developing features such as granulation, flowage, distortion, rupture of mineral grains and slaty cleavage. Cataclastic metamorphism combined with thermal metamorphism over wide area gives rise to regional metamorphism, developing fabrics such as banded gneiss and schistose structure. Plutonic metamorphism is deep-seated regional metamorphism. When rocks undergo adjustment more than once, it is known as polymetamorphism.

A rock mass is said to have suffered from a particular metamorphism, by distinguishing characteristic minerals found in each type and such other field evidences like foliage, schistosity or banded structure.

For examples, minerals like staurolite and garnet (grossularite and almandine) are restricted to schists and other deformed rocks, whereas andalusite and cordierite are found only in thermally metamorphosed rocks which has not suffered from directed pressure. Grossularite is especially characteristic of metamorphosed impure calcareous rocks; almandine of schist and metamorphic rocks containing alumina and iron. Distinction between one particular type of metamorphism and other is not so sharp as it should have been because a rock mass, during the vastness of time, since it was formed could not remain unaffected by other cycles of strong or mild metamorphism. Nevertheless, a particular mineral assemblages provide some clue to this effect. Broadly three important facies, namely, Green schist facies or Chlorite facies, Biotite facies, and Eclogite facies are recognised in the metamorphic rocks indicating formation of different minerals under each facie in order of increasing temperature and pressure.

A sequence of index minerals formed with increasing temperature has been established from the field observations. These are:

(1) chlorite;
(2) biotite;
(3) almandine;
(4) staurolite;
(5) kyanite, and
(6) sillimanite.

A great deal of data have been studied about the effect of heat, hydrostatic pressure and directed pressure on minerals and rocks in order to understand metamorphism. It has been established by experiments that at constant volume, rise in temperature promotes development of those minerals which are formed from the absorption of heat. Heat also displaces volatile matter and tends to increase in volume. Minerals and rocks affected by thermal metamorphism, by and large, become anhydrous or contain very low percentage of hydroxyl molecule. Rise in pressure on the other hand displaces the equilibrium of the original rock in the direction of diminution of volume. The rocks and minerals thus formed acquire high density. The stress act in the same way effecting diminution of volume although it favours production of quite different minerals. Uniform pressure and thermal metamorphism are found to favour formation of minerals such as plagioclase (anorthosite), orthoclase, augite, andalusite, sillimanite, cordierite and spinel. These are called anti-stress minerals. They become unstable under stresses and transform into different minerals altogether. In fact chemistry of metamorphism is quite immense and complex. Interaction of different minerals may give rise to same mineral by different metamorphic processes.

One important characteristic of metamorphism is that under its influence minerals tend to be simpler in texture. Twin crystals or zoning are rarely found in metamorphic rocks. The formation of new and stable minerals is governed largely by the phase rule depending upon the original mineral composition of sedimentary and igneous rocks. The adjustment in mineral constituents takes place in solid phase or solid state without undergoing remelting.

Depth of intrusion is quite an influencing factor in thermal metamorphism because at depth the initial temperature remains quite high, and the rate of cooling becomes slow which produces marked effect of metamorphism. Depending upon the initial heat and depth, the effect of metamorphism, in the formation of minerals and rocks, have been grouped under three zones, as follows:

(1) Epi zone—lower depth—300°C—strong shearing effect.

(2) Meso zone—medium depth—300 to 500°C—mild shearing effect.

(3) Kata zone—deep-seated—above 500°C—no shearing effect.

In general the rocks most susceptible to thermal metamorphism are argillaceous and carbonaceous rock. Argillaceous sediments compared to carbonaceous sediments are more susceptible to metamorphic processes. The chemical composition of the argillaceous include silica, alumina, magnesia, calcium oxide, sodium oxide, potassium oxide and thermal metamorphism make them to unite to form such minerals like andalusite, kyanite, sillimanite, cordierite, staurolite, pyrope (magnesium garnet), many of which are not known in igneous rock. Argillaceous (silicious) sedimentary rocks under the influence of contact metamorphism changes to quartzite. The most striking metamorphic changes take place when igneous rock is intruded into impure limestone which normally contains varying amount of impurities like quartz, clay, dolomite and iron oxides. These under the influence of heat and pressure combine to form new minerals. Quartz and limestone may react to form wollastonite, $CaSiO_3$. Limestone and dolomite may react with quartz to form pyroxene $(Ca, Mg) SiO_3$. Aluminium of clay enter into reaction with magnesia and lime and forms spinel, $MgAl_2O_4$, and with calcium and silica grossularite, $Ca_3Al_2Si_3O_{12}$. Limestone itself under pressure recrystallises into marble. Many basic igneous rocks break down easily into chlorite under the influence of metamorphism.

Stress becomes a dominating factor in the epi and meso zones. It lowers the melting point of minerals and increases their solubility, a powerful factor in recrystallisation. It has been established that solution takes place at the point of greatest pressure in a crystal with concurrent precipitation at the point of least pressure which has an important bearing in the origin of parallel schistose and foilated structure in metamorphic rocks. Stress favours production of minerals of mica group (muscovite and sericite) and albite among felspar, minerals of epidote and zoisite groups, tremolite along with kyanite, staurolite and chloritoid and talc. These are commonly called stress minerals.

The chief minerals of basic igneous rocks, anorthite, pyroxene, olivine and iron bearing minerals viz. ilmenite and magnetite are susceptible to metamorphic changes and these adapt well to the effect of progressive metamorphism. This phenomenon is most commonly exhibited by gabbro, a basic rock which converts into eclogite, a coarse grained granulose rock consisting of garnet and pyroxene. The garnet in eclogite is produced by reaction of fosterite and anorthite as shown under.

$$\underset{\text{Fosterite}}{Mg_2SiO_4} + \underset{\text{Anorthite}}{CaAl_2\,(SiO_4)_2} \rightarrow \underset{\text{Garnet}}{CaMg_2Al_2\,(SiO_4)_3}$$

Common Metamorphic Rocks

The most common metamorphic rocks are gneiss, usually formed from granite, but it may have sedimentary origin also. In gneiss, the composition remains basically the same as that of granite but the minerals quartz and felspar show parallel structure separated by mica. Various names have been given for different varieties *viz.* biotite gneiss, hornblende gneiss, banded gneiss, etc.

Next to gneiss, mica-schist is the most common rock. It may form from acid igneous rocks or from phyllite beds. Mica-schist is composed mainly of quartz and muscovite or biotite mica and carry characteristic minerals such as garnet, staurolite, kyanite, epidote, hornblende etc. Metamorphism of basic igneous rock give rise to various other kinds of schist rocks, chiefly, talc-schist, chlorite-schist, amphibolite-schist.

Other common metamorphic rocks are slate, quartzite and marble. Slate is formed from shale retaining the characteristic cleavage of the original bed. These permit them to split up into thin and broad sheets. They are commonly of black colour, sometimes may be green, yellow and red. Slate is usually found in the region where sedimentary beds had been affected by intense folding by cataclastic metamorphism. Quartzite is composed essentially of silica, cemented together forming hard and compact mass. Marble is a crystalline limestone. It is usually of white colour and may show an array of pleasing colours depending upon impurities present. Slate, quartzite and marble are extensively used for industrial purposes. Slate, as we know, is extensively used for roofing tiles and for making children's school slate. Quartzite serves as an excellent silica refractory material and source of glass sand. Marble is well known decorative building stone.

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Formation of Mineral Deposits

This chapter deals, to some extent, with the various processes which lead to the formation of mineral deposits. Although the entire earth's crust can be regarded as made up of minerals still it cannot be regarded as a mineral deposit. An occurrence of a mineral becomes deposit only when its concentration in known dimension is sufficient enough to warrant its mining and utilisation. A deposit is always localised. It may be large or small, depending upon the total quantity of reserves available. A mineral may be metallic or non-metallic. Metallic minerals are those which are valued for metal content and from which metals are extracted. For example, chalcopyrite for extraction of copper metal; haematite for iron; galena for lead; sphalerite for zinc, etc. Non-metallic minerals evidently are those which are not valued for metal content but are useful in various industries. Some of the important non-metallic minerals are limestone, dolomite, mica, asbestos, barytes, talc and clays. A metallic mineral is most commonly signified by the word 'ore' or 'ore mineral'.

Uptil now, nearly 2000 minerals have been identified in the earth's crust, most of them are of rare occurrence. About 30 minerals go to form the most common rock types. Commercial application of hardly 200 minerals has been established so far. These are known as economic minerals. Only about 25 metals are of use, out of which seven, namely, iron, manganese, aluminium, copper lead, zinc and tin form the bulk consumption in industries. The bulk of the minerals formed consist essentially of eight principal elements. The minerals formed out of the remaining elements are far less in distribution. Gold and platinum invariably occur in metallic state *i.e.* in native form. Native gold usually contains a small quantity of silver in solid solution. Native platinum contains invariably five metals of its group, namely, palladium, rhodium, ruthenium, osmium and iridium. Silver, copper and mercury also occur in native form but they commonly occur as sulphides. Sulphur, diamond and graphite are the only non-metallic minerals which occur in elemental form. Minerals are not formed daily; neither their formation is a day's work. It took several millenniums to form them. Field evidences indicate that a group of minerals, ore minerals or metals were deposited in different eras, periods and epochs by diverse and complex processes. The whole earth's crust may be regarded as a vast laboratory of the Nature, where it can produce varieties of minerals—a wonderful bounty for mankind.

What we try to study under the Science of Geology is to establish how mineral deposits were formed, where do they occur and their genetic relation to particular rock types and environment. No two deposits have been found to be identical. Years of field work on the various known mineral deposits and laboratory experiments, have established it clearly that mineral deposits are connected genetically to particular rock types and were formed in certain environment during different geological periods. In their formation, they followed definite law of mineralisation depending upon heat and pressure, solubility of particular minerals in presence of others, melting points, natural affinity of one element to another, and chemical composition of the magma at different times of consolidation. It is further found that distribution of elements is controlled not by their densities or atomic weight only but by their affinities for the major phases of tectonic movements. The distribution of elements within these phases depends upon chemical affinity. Although magma is the source of all elements and consequential formation of many minerals, it is not the source of all minerals, known in the earth's crust. There are a large number of minerals which are found to be formed by processes other than magmatic ones. There are some minerals which are formed by more than one processes and thus are found to occur in different geological settings. The students are advised to read this chapter with open mind. The modes of occurrence and methods of formation are detailed here based on the field evidences recorded so far. The impression should be carried in the memory and subjected to constant scrutiny and analysis upon new evidences if recorded in the field. The whole complexes of mineral formations can be summarised under:

(*i*) igneous:
(*ii*) sedimentary;
(*iii*) metamorphic;
(*iv*) weathering; and
(*v*) supergene (secondary) enrichment.

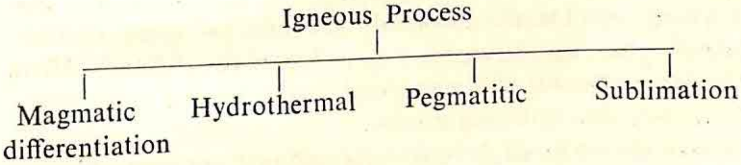
The minerals formed by the igneous process *i.e.* which result from the cooling of magma are regarded as primary and those formed subsequently by processes other than igneous as secondary. Minerals of igneous origin as said before are always genetically connected with specific rock types. For example, chromite (ore of chromium), garnierite (ore of nickel), platinum, diamond, ilmenite (ore of titanium) are always found to occur with ultra-basic to basic intrusive rocks while ores of tin, tungsten, cobalt, molybdenum, bismuth, antimony, mercury, lithium, copper, lead and zinc, and gold and silver with acid to intermediate intrusive rocks. It is, therefore just futile to search for chromite in acid rocks and cassiterite (tin ore) in basic rocks. Some minerals, for example, apatite and magnetite are found to occur in basic to acid rocks but by and large their affinity is more towards basic rocks. Similar is the case of copper sulphides. Garnierite, an important ore of nickel is always found associated with rocks of ultrabasic character. On the other hand, another nickel mineral pentlandite is invariably found associated with sulphide mineralisation of intermediate to acid characters. The formation of secondary mineral deposits is largely governed by environmental conditions.

More and more of field data provide us ample evidences that mineral deposits, whether of primary or secondary origin, were formed in definite pattern adhering to the normal rule of acqueous solution under specific conditions. In addition to these, other controlling factors for mineralisation are structural, lithological and stratigraphical. Structural control is very significant in trapping magma for casting off its mineralised fractions. The deformation *i.e.* the weaknesses in the earth's crust like fracture, fissure, shear zone, fault, fold, bedding plane, depression, basin and geosyncline are the repository homes of minerals. The rising magma could pervade through these weaker zones and leave behind mineralised portion. Therefore, most of the economic minerals of igneous origin, are found in areas having suffered great tectonic movements. More often mineralisation is found disseminated in host rock covering wide area. Such type of the deposit is formed when the magma pierce through the interstices of host rock. Great basins or depressions were the seat of deposits of sedimentary origin.

It is to be borne in mind that it is not necessary that all magmas should be laden with economic minerals. Most of them are unproductive and mainly form rock bodies. It is the greatest enigma which has not been understood as to why all magmas do not carry mineral constituents in required proportions. However, this answers precisely the reason why mineral deposits are unevenly distributed and narrowly localised.

IGNEOUS PROCESS

The mineral deposits formed by igneous process are grouped under three headings:



Magmatic Differentiation

Magma is the seat of origin of all minerals formed by igneous and metasomatic process as well. The magma having been forced up towards the surface, gets losing temperature. In this process, fractional crystallisation takes place, and the melt differentiates into heavier and lighter fractions, the heavier portion remains at the bottom and lighter comes on the top. The heavier portion forms the basic and the lighter acid magmas. Fractional crystallisation is a process whereby magma gives rise to contrasted fractions by separation of crystals from the liquid in a cooling magma. The minerals of high fusion point, depending upon their saturation in the melt, start crystallising and segregating out the moment temperature falls below the fusion points of respective minerals at the existing pressures. Field observations indicate that the earliest formed minerals are chromite, platinum, diamond, vanadium minerals, ilmenite, magnetite and apatite. They are always associated with ultrabasic to basic rocks like dunite, peridotite, gabbro and norite. Magnetite and apatite are more pronounced in basic rocks than ultrabasic. In some cases ilmenite gets concentrated in basic rocks. When such magmas at the time of segregation get injected into the adjoining rocks (country rock) they give rise to individual deposits. They may form massive ore bodies, and occur as lenses, tabular form or disseminated throughout the rock bodies. There are possibilities of magma getting injected at early, middle or late magmatic differentiation stages. Depending upon the stages, the injecting magma give rise to different mineral deposits. Chromite deposits are unimpeachable examples of early magmatic segregation. The most common example of disseminated type of deposit in basic rock is offered by diamond. Diamond is found always in basic eruptive pipe rock commonly known as 'Kimberlite' pipe, a variety of peridotite. The pipe rock contains crystals of diamond disseminated throughout the rock mass. The average incidence of diamond in kimberlite pipe rocks of Republic of South Africa is 0.33 carat and that of Majhgawan (Madhya Pradesh) 0.1 carat per tonne of rock. Chromite bearing Merensky reef of Republic of South Africa containing valuable platinum metals is the finest known example of early magmatic segregation.

Other examples of deposits originating from basic magmas are: vandium bearing titaniferous magnetite ores of Mayurbhanj, Orissa; ilmenite-magnetite occurring in anorthosite in Adirondack, New York; ilmenite-hematite occurring in anorthosite in Allard Lake, Canada; apatite vein containing magnetite, biotite and chlorite in Singhbhum copper belt; and apatite veins occurring in a zone of magnetite-vermiculite in Srikakulam district, Andhra Pradesh. The huge magnetite deposits of Kiruna, Sweden have been accumulated as a late differentiation at depth and later injected, Kiruna magnetite contains high phosphorus as mineral apatite. The phosphorus content varies from less than 0.5 per cent to over 2 per cent. In the basic magma, the water vapour along with chlorine play an important role as mineralisers. Chlorine combines with apatite to form chlor-apatite $3Ca_3(PO_4)_2.CaCl_2$. In presence of fluorine, it forms fluor-apatite $3Ca_3(PO_4)_2.CaF_2$. Water vapour may react with magnetite to form hematite: $2Fe_3O_4+H_2O=3Fe_2O_3+H_2$. Apatite and magnetite are most often found as accessory minerals in all types of igneous rocks. Valuable metallic deposits are also found associated with lavas of all ages. Vesicular basalt, containing native copper filled in vesicles together with calcite, epidote, chlorite, zeolite, is of special interest occurring in Lake Superior region, Michigan in USA. Important deposits of gold-silver are found in andesite rock in New Zealand, Sumatra and Comstock in Nevada, and Guanajnato and Pachwa in Mexico. Gold-silver deposits have also been found in rhyolite and trachyte in Tonopah in Nevada.

The residual melt after being stripped off earlier formed minerals, becomes enriched in silica and differentiates into melts of intermediate and acidic character. The unsaturated melt is responsible for the formation of minerals of felspathoid group and forms most common syenite and diorite rocks. Magmatic corundum and its gem varieties ruby and sapphire are found in syenite rock. Mineral zircon is found to occur from intermediate to acid rock granite.

It is of interest to note that all sulphide minerals like chalcopyrite, covellite, chalcocite, bornite, tetrahedrite, enargite, greenockite, pentlandite, galena, zinc blende, cobaltite, sulphide of bismuth, antimony, arsenic, molybdenum and mercury are invariably associated with intrusive rocks of intermediate to acid characters like syenite, diorite, monzonite, granodiorite and granite, and carry accessory minerals like magnetite, zircon, pyrites and apatite. It has been most commonly observed that syenite and nepheline-syenite often contain minerals of rare earth group such as phosphate of cerium, lanthanum, yttrium forming mineral monazite with uranium and thorium. Gold is always associated with intrusive acidic rocks and occur as disseminated particles and nuggets with blue quartz. Gold containing silver also occurs associated with copper sulphide minerals. Singhbhum Copper belt extending for a distance of 130 km from West to East is a classic area for studying modes of mineralisation as well as their structural and lithological controls. The mineralisation is associated with thrust zone. There are number of shear zones parallel to the main zone. The structure is complicated due to intense folding and shearing all round thrust zones. The area south of the thrust zone is unmetamorphosed and commonly known as Iron Ore series and area lying north of the thrust zone is metamorphosed and called Chaibasa stage, in the Indian stratigraphy. Three distinct periods of mineralisation are recorded, *viz.* (*i*) apatite-magnetite mineralisation; (*ii*) uranium mineralisation, and (*iii*) sulphide mineralisation. The sulphide phase appears to have occurred after prolonged period of biotitisation and chloritisation of the earlier formed rocks. The mineralisation is associated with thrust zones and copper mineralisation is controlled by series of isoclinal folds and shear zones. The sulphide minerals are associated with Arkasani soda granite (granophyre).

The minerals of rare and scarce elements are always found as co-product occurring with sulphide ores of copper, lead, zinc and they are never independently mined. For example, caesium, gallium, rhenium, germanium, indium, selenium, cadmium, bismuth are more often recovered as co-products during smelting and refining of copper-lead-zinc melts. Tellurium, a semi-metal is recovered from gold. Gold and galena (lead ore) are invariably a source of silver as co-product. Similarly cadmium is invariably recovered from zinc ore.

From experience, it has been observed that intrusive or extrusive activities which took place in different geological periods gave rise to distinct types of rock. All igneous activities whether intrusive or extrusive may not give rise to the formation of economic minerals. But certain igneous activities had oregenic (metallogenic) relations, each giving rise to different mineral formations. For example, gold is universally found to be associated with acid intrusives from Pre-Cambrian to Tertiary, on the other hand mineral cinnabar (mercury sulphide) is universally found to be resulting from the acid intrusive rocks of Tertiary era only. Therefore, a study of the oregenic cycle of each country or region is very important in search of mineralisation. It should be remembered, that igneous activities in particular period, although widespread, did not cover entire surface of the globe but were localised to few regions of weaknesses prevailing in that period only. Therefore, oregenic activities followed different patterns in different periods in different regions.

Hydrothermal

Most of the non-ferrous deposits are formed by this process as fissure fillings. Deposits of hydrothermal origin are found occurring in veins or forming thin sheets or even widely but evenly distributed like porphyry copper ore deposits. For details see also 'metamorphic process'.

Pegmatitic Phase

The residual portion of the magma is of immense value in the formation of minerals. The separation of nonvolatile mineral constituents enriches the residual portion with volatile components. This phase of magmatic differentiation is known as pegmatitic which contains minerals of high silification and is usually charged with vapour and gases like chlorine, fluorine, boron, iodine, bromine, phosphorus, and sulphur. These vapour and gases play an important role in the formation of minerals containing hydroxyl and volatile elements. The residual melt after getting injected into the country rocks gives rise to pegmatite deposit. Pegmatite is the source of rarest elements and many useful minerals and hence it is called 'nature's museum'. The chief minerals of pegmatite are quartz, felspar and mica, and are usually found to contain ores of tin, tungsten, molybdenum, copper, antimony, arsenic, lithium, beryllium, bismuth, columbium or niobium, uranium and thorium. Tourmaline, apatite and fluorspar form the accessory minerals. There appears to exist one distinct relationship between a pegmatite and the country rock. Wherever pegmatites have intruded country rock other than mica-schists, they are found rich predominantly in felspar. On the other hand pegmatites intruding mica-schist are usually found to contain muscovite mica, as if mica of the country rock imparts leavening effect in the formation of minerals of mica group. It has been observed by examining numerous pegmatites containing muscovite and beryl that predominance of one mineral considerably reduces the economic workability of the other. It means that muscovite and beryl are formed at the expense of each other. Beryl bearing pegmatite traversing biotite-schist and talc-schist rocks give rise to the formation of emerald, a gem variety of beryl, as it is found in Ajmer and Udaipur which are chief producing areas in India. Occurrence of emerald is more predominant at the contact zone of talc-schist than biotite-schist. Lithological relations of mineral formation is a very interesting phenomenon which should arouse interest in readers for study.

Sublimation

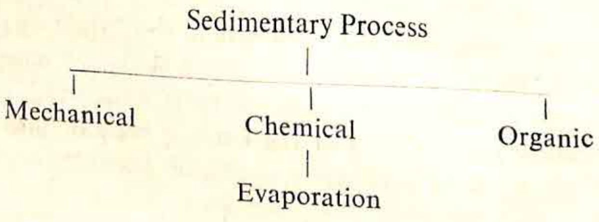
It is a matter of common observation that volcanoes emit through craters and subordinate vents (fumaroles) copious amount of vapour and volatile metals in combination with halogens also called mineralisers like chlorine, bromine, boron, fluorine, sulphur etc. Emancipation of gases continues for considerable period even after dormancy has ceased. The interaction of these slowly escaping gases often give rise to deposition of minerals as sublimates around the vent or crater. Sulphur and borates are the most common minerals formed as sublimates. Sulphur filling craters are mined in Japan and Italy. In the latter country, sassoline—a native boric acid H_3BO_3 is found associated with sulphur. Sulphur is deposited by the following reaction:

$$2H_2S+SO_2=2H_2O+3S$$

Some occurrences, mostly as incrustations, of copper ores, cinnabar, stibnite and realgar are also noticed around fumaroles, but they do not form economic deposits. Except borates and sulphur, no economic deposit of other minerals has been noticed which was formed out of sublimation process.

SEDIMENTARY PROCESS

Sedimentary process gives rise to several distinct minerals which are unknown in the list of minerals originating from igneous or metamorphic process. It is very true of minerals formed by chemical and organic processes. The methods involved in the formation of mineral deposits under sedimentary process can be split into three main heads and one sub-head as under:



Mechanical

It is a process by which many valuable minerals and metals having high resistance to solubility and abrasion, sparsely distributed and disseminated in different rocks, after being dislodged from the parent rocks by the action of weathering, get assorted and concentrated. This process is similar to the process of gravity separation by flowing water. Rain and river water carry dislodged particles along with their flow. The flow of the particles is governed by their respective specific gravities.

The nature of mineral accumulation determines the terrain through which the river has flowed; for it could carry minerals only of those bed-rocks through which it traversed. The transported material accumulates in the valleys of rivers, lakes or on sea beaches. The resulting gravel and sand deposits are accordingly classed as alluvial, lacustrine and marine. Such deposits are generally referred to as 'placer deposits'. The places at which the river takes long meander in the course of its journey are favourable sites for accumulations. Gold, on account of its high sp. gr. (sp. gr. 16) gets sorted out much earlier than remaining minerals and metals. If the bed rocks consist of steeply dipping schist and slate, their foliage act as a natural riffle in trapping the particles. An understanding of the present and past drainage pattern is important in search of deposits of mechanical origin. Many placer deposits are being extensively exploited all over the world; of which the deposits of cassiterite, platinum, gold, diamond, ilmenite, rutile, zircon, garnet, monazite, sillimanite, magnetite, wolfram, chromite, topaz, spinel and quartz sand are important. A finest example of placer deposit is offered by beach sands of Kerala and Tamil Nadu containing extensive resources of ilmenite, rutile, monazite, sillimanite and garnet. Such beach sands are mined in several countries, *viz*. Australia, USA and Sierra Leone. Nearly entire production of cassiterite (tin ore) is obtained from gravel beds and dredging sea sand in Indonesia, Malayasia, Thailand, Tasmania, Niger, Cornwall, Bolivia and Republic of South Africa. Diamond is worked in considerable quantities from the gravel beds and sea-sand in South-West Africa. In India, gravel bed deposits at Ramkheria in Panna is an important source of diamond. Occasionally diamond crystals have been picked up from Mahanadi river in Orissa. Panning of gold from the sands of Subarn Rekha river is the usual feature in South Bihar. In fact, placer deposits occur in river system of every part of the world. The largest gold producing area in the world at Witwatersrand in the Republic of South Africa is a placer deposit, occurring in alternating beds of shale, quartzite and conglomerate of 6,000 metre in thickness. Beach sands containing hematite, magnetite and ilmenite cover wide area of southern island of New Zealand. Magnetite sands are recovered from sea coast in Japan. Platinum placers are worked on the river Iss and rivers draining the eastern slopes of Ural mountains. Platinum occurs in association with chromite and magnetite.

Chemical

There is hardly any mineral which is not affected by surface water. Generally minerals are insoluble in water at normal temperature and pressure except salt-minerals of potassium, sodium and boron; but, surface water, flowing through different terrain and after getting charged with carbonic acid by absorbing carbon dioxide, humic acid from plants, and sulphuric acid from rocks containing sulphides, becomes effective solvent, and dissolves or leaches out, to some extent, almost all minerals. These mineral bearing solutions are carried away by river and rain water to sea, lakes, lagoons and swamps. Sea is the largest repository of minerals in solution. Analysis of sea water indicates that it contains 3.5 per cent of solids in solution by weight, of which sodium chloride, magnesium chloride and calcium sulphate are most abundant. In fact, sea water contains traces of all elements. The principles of sedimentary formations are the chemical breakdown of rocks and minerals and formation of the new ones.

It should be understood that all earliest great trough were either geosynclinal basins or inland seas, cut-off later by regression of the main sea. These depressions were the areas of accumulation of minerals in solution or mechanically transported material. Chemical reaction got some of the minerals precipitate out of the solution. With the passage of time and change of climate, the basins started drying up and became shallow by evaporation resulting in the precipitation and deposit of more soluble minerals. The latter class of deposits are commonly known as evaporites. Gypsum, rocksalt, borates etc. are examples of evaporites.

Most important mineral deposits of chemical origin are dolomite, limestone, kankar, hematite, manganese ores (except silicate minerals), gypsum, anhydrite, calcite, rocksalt, saltpetre, nitre, borates, phosphorites, celestite, strontianite, magnesite, brucite, epsomite, kieserite, agate and chert or chalcedony. Sedimentary deposits usually cover wide area although cavity filling and vein deposits are not uncommon. Individual deposits of hematite (iron ore), limestone, dolomite and gypsum occupy several square kilometres area with beds several metres thick. Pre-existing rocks were the source of the chemical constituents of all the above minerals. For example, calcium might have been derived from rock-forming minerals anorthite, calcium pyroxenes and amphiboles; sodium and potassium from felspars and felspathoids; magnesium from basalt, pyroxenites and dunites; boron chiefly from volcanic vents and fumalores deposits; iron from iron pyrite (FeS) and breaking up of ferromagnesium silicates.

Calcium, iron and manganese are dissolved and carried away as bicarbonates. Experiment shows that manganese is more soluble than iron in bicarbonate solution. Silica is dissolved in most alkaline water. Most of the elements are transported as colloids and play an important role in the formation of mineral deposits.

As a rule, salts are precipitated in the reverse order of their solubility, the least soluble first and the most soluble last. In sea water, during evaporation, dolomite $MgCO_3.CaCO_3$ which is the least soluble first precipitates out; then after evaporation has increased the concentration of dissolved salts, three times or more, limestone (calcite) $CaCO_3$, and magnesium carbonate (magnesite) $MgCO_3$ begin to precipitate out. Hydrated calcium sulphate (gypsum) $CaSO_4.2H_2O$, precipitates below 42°C whereas anhydrous calcium sulphate (anhydrite) $CaSO_4$ at about 25°C. Most soluble salt minerals *viz.*, rocksalt NaCl, thenardite Na_2SO_4; Mirabilite $Na_2SO_4.10H_2O$; glauberite $Na_2SO_4.CaSO_4$; epsomite $MgSO_4.7H_2O$; natron $Na_2CO_3,10H_2O$; trona Na_2CO_3-$NaHCO_3.2H_2O$; carnallite $KCl.MgCl_2.6H_2O$; kainite $KCl.MgSO_4.3H_2O$; polyhalite $K_2SO_4,MgSO_4.2CaSO_4.2H_2O$; sylvite KCl; nitre KNO_3; alunite $KAl_2(SO_4)_2.(OH)_6$; kieserite $MgSO_4$.

H_2O; borax $Na_2B_4O_7.10H_2O$; kernite Na_2O, $2B_2O_3.4H_2O$; colemanite $Ca_2B_6O_{11}.5H_2O$; boracite $5MgO.MgCl_2.7B_2O_3$ etc. precipitate out in the last. It is not necessary that each sedimentary deposit should give rise to all the mineral formations. In most of the cases, the final desiccation at which soluble sodium, potassium and boron salts could be precipitated, did not reach.

Highly soluble salt deposits of sodium, potassium and borates are found in dried up lakes in desert region only where the rainfall is practically negligible. Several playas (dried up shallow basins) in north Chile and Tibet contain valuable deposits of borates. Saturated solutions of calcium bicarbonate infiltrating through fissures and cracks give rise to calcite (crystalline) deposits owing to the loss of carbon dioxide.

$$Ca(HCO_3)_2 = \underset{\text{Calcite}}{CaCO_3} + H_2O + CO_2$$

The same solution dripping from the roof of caverns of limestone rocks forms concentric ring of calcite hanging like pendant columns. These are known as *stalactite* and those growing upward in a cone shaped from the floors of the caverns are known as *stalagmite*. Calcareous tufa, calc tufa or travertine is the name given to calcite deposits of cellular structure. Dolomite is also formed by the chemical replacement of calcium ions by magnesium ions. This is a common phenomena observed in the limestone country which contains variable proportion of magnesia. Kankar is formed by the desiccation of rising ground water containing dissolved lime as bicarbonate.

Hematite deposits occurring in alternate bands with cherty silica, known as jasperite, is now believed to have been formed by microscopic plants of earliest Proterozoic era which were habitantly capable of extracting and precipitating iron and silica. Iron readily combines with oxygen to form Fe_2O_3. Iron carbonate (siderite, $FeCO_3$) which is found in the barren measures of Gondwana is believed to have been formed by the following reaction, by losing carbon dioxide.

$$Fe(HCO_3)_2 = \underset{\text{Siderite}}{FeCO_3} + H_2O + CO_2$$

The bog iron ore (limonite) is formed by the hydration of siderite or hematite in marshy area. Many forms, like oolitic, pisolitic, concretionary, botryoidal and banded which a mineral exhibits are now considered to be of colloidal origin. Such forms are usually found in manganese ore, agate, onyx, chalcedony, opal, limestone, iron ore and phosphorite. Commercial deposits of manganese ores are entirely of sedimentary origin, later metamorphosed. Manganese goes into solution both as bicarbonate and phosphate and gets readily oxidised to form pyrolusite MnO_2 which is the most common ore of manganese. Hydration converts it into psilomelane $H_2O.MnO_2$. Other important manganese ores are braunite $3Mn_2O_3$. $MnSiO_3$ and manganite $Mn_2O_3.H_2O$. Manganese ore bodies occur as band and lenticular masses enclosed in metamorphosed sediments such as manganiferous quartzites, schists and marbles. In India two distinct series, namely, Gondite and Kodurite of Dharwar age are recognised containing metasediments of manganese ores.

Phosphorite or rock phosphate is the most important source of phosphorus. It has variable chemical composition assigned most commonly as $Ca_3(PO_4)_2$ with small percentage of chlorine and fluorine just like apatite of igneous origin. Phosphorite is found as bedded and disseminated in all geological formations of marine origin. The geological evidences indicate that the ancient seas or whenever there has been marine transgression and the sea water was drying up, favoured formation of phosphorite beds. The ideal place for its formation has been found bordering Cratonic rock (ancient platform) and continental slope up to 500 m depth from the surface. Better grade has been found from the miogeosynclinal deposits nearest to the platform. The most governing factor for the precipitation of phosphorite is found when the sea water tended to be slightly alkaline; as the phosphorite bed is invariably found occurring after deposition of quartzite and chert; the transitional zone between cherty shale, black carbonaceous shale being the most favourable horizon. Co-precipitation of limestone and dolomite is also in evidence, even before and after the formation of phosphorite depending upon the then physico-chemical conditions. Lithological facies like dolomite limestone, chert and carbonaceous shale are established to be the first class geological criteria for search of phosphorite. The presence of carbon is indicative of the existence of reducing condition. Sea water is regarded as the chief source of phosphorus in this case; the other source may be the Cratonic rocks themselves. Phosphorus is the most important element of bone and food for plant, therefore, it is invariably found in all organisms. Their decay gives rise to soluble salts, which reacting with calcium solution forms phosphorite. Some sea fossils have been found to contain as much as 35 per cent P_2O_5. Very important point is noted universally in case of phosphate rock that it is always associated with fluorine in some proportion usually between 3 and 4 per cent in terms of calcium fluoride; therefore, the condition governing its precipitation is considered related to and caused by such marine volcanism emitting fluorine gas. Thick beds of phosphorite formed by this process are widespread in occurrence, covering greater part of North Africa, Florida in USA, Brazil in South America, Rajasthan, U.P., M.P., Bihar and Tamil Nadu in India. A crypto-crystalline variety of phosphorite is known as cellophane. Such variety is difficult to treat for beneficiation.

Organic

Minerals formed by organic process are both inorganic and organic in nature. In this process the countless organism that live in the sea make most invaluable contribution. Most of the marine creatures utilise calcium carbonate dissolved in sea water for making their hard parts, and leave behind vast accumulation of shells, skeleton or other hard parts forming varieties of limestone. Foraminifera, bryozoa, porifera, echinoderma, polyzoa, brachiopoda, lamellibranchia, gasteropoda and cephalopoda are the chief invertebrates which gave rise to limestone beds in ancient sea. Friable limestone commonly known as chalk is of organic origin. Unconsolidated bed of limeshell found in Vembanad Lake of Kerala, is an important source of lime for the manufacture of cement and calcium carbide. Such beds are found in several places in Chickmagalur district in Karnataka.

Coral limestone, providing a source of pure calcium carbonate for chemical industry, is well known. Deposits of coral limestone occupy vast areas in shallow seas in temperate regions. The great Barrier reef in the east and north coasts of Australia forms a ridge of coral limestone on the sea bottom stretching over 1,600 km in length. Coral limestone is found in stretch of 130 km length on the coast of Tamil Nadu, which is being extensively mined.

Another important inorganic mineral formed by organic process is diatomite. Diatoms are microscopic plants which extract silica dissolved in sea water and grow as siliceous plants which, on decay, leave behind thick accumulations of silica deposits. It has an immense use as filter-aid in filtering out colloidal substances. Likewise, radiolarians extract silica and give rise to deposits called radiolarite. Such deposits are found varying from few mm to about 300 metres in thickness. Unconsolidated deposits of diatoms are known as diatomaceous earth and, when consolidated, as diatomite. Similar is the case with radiolarian earth and radiolarite. Radiolarian silica consists of opaline skeleton or tests. Diatomite is divided into marine and fresh water types. More than 10,000 species of diatoms have been recognised.

Silica is dissolved in most river water at high alkalinity. Low pH, low temperature and rising salinity favour precipitation of silica as gel. Bedded cherts are believed to have been formed by direct precipitation of silica and silicification of radiolarian and diatomaceous earths. Submarine volcanic eruptions are also likely source of silica. Banded structure in agate and onyx, which are varieties of chalcedony, are produced by rhythmic precipitation of silica in colloidal solution.

Ooze is an expression of physical characteristics of calcareous and siliceous deposits formed, beyond continental shelf, by sea organisms. Calcium carbonate is more soluble than silica in sea water and hence calcareous oozes do not reach such depths as the siliceous oozes. In deep sea, even silica dissolves before reaching the bottom. Therefore, deepest part of the sea is often found to contain airborne or volcanic dust layered on the bottom called red clay.

Organic minerals formed by organic processes are chiefly coal and petroleum.

Coal

Geological evidence provides ample justification that the coal has been formed from the decay of terrestrial plants. Coal contains variable proportions of carbon, hydrogen, oxygen and nitrogen forming aromatic compounds. The chief constituents of plant material are cellulose and lignin containing minor components of proteins, essential oil and organic acid and their salt, tannins etc. The empirical formula of cellulose is $C_6H_{10}O_5$ whereas that of lignin $C_{12}H_{18}O_9$. The structure of lignin is aromatic whereas cellulose is aliphatic. On this account, many authorities believe that lignin is the parent of coal. The bacterial action in reconstituting humus from vegetal matters, a complex mixture of amorphous organic substance is regarded essential as it forms the beginning of coalification. Layered coal seams were formed under the influence of hydrostatic pressure and geothermal heat. It has been well established that coal was deposited only in swampy regions or fresh water lakes during the fixed geological time beginning from Carboniferous up to Tertiary age. In this period, forest trees grew in abundance in swampy areas which had to suffer several phases of intermittent yet slow sinking. One phase gave rise to the formation of one coal bed and again the area was brought under sedimentation by river flow, giving rise to shale and sandstone deposits thus burying the coal bed formed earlier. Good amount of sediments deposited in the basin of swampy areas gave rise to luxuriant growth of trees which after dying out formed new seam of coal deposit. Several cycles of such formations are recorded in different parts of the world. In India, as many as 25 cycles are noted in Permian period. The occurrence of coal is more pronounced in Carboniferous and Permian periods of Palaeozoic era than Mesozoic era. Again, the occurrence of coal in Tertiary era is more pronounced than that of preceding Mesozoic era. It clearly indicates that, climatic conditions for the growth of forest trees were much more favourable in Tertiary and towards the end of Palaeozoic era than those obtained during Mesozoic.

Four ranks of coal are recognised, namely: peat, lignite, bituminous and anthracite. Peat is the earliest form of coal. A rank of coal indicates the extent to which vegetal matter has suffered pressure and heat. Carbon content increases with the increase in rank of coal. Peat contains about 55 per cent carbon whereas, the anthracite about 97 per cent. On the other hand, the percentage of hydrogen and oxygen in the form of volatile matter decreases with the increase in rank, as they are driven out under heat and pressure. Some percentage of nitrogen occurring in coal is regarded as derived from bacteria responsible for biochemical action, as neither cellulose nor lignin contains nitrogen which is an important component of coal. The ash content in the coal is an assimilation of the sediments during the course of decay and decomposition of the vegetal matters.

Bituminous is divided into two categories *i.e.* coking and non-coking. Coking coal forms lumpy and porous mass when heated in total absence of air at a temperature of about 925°C. Non-coking coal becomes friable under the same condition and hence it is largely used for generating heat. What imparts such property is the matter of great scientific investigation but, it has been found that whenever the ratio between hydrogen and oxygen in a bituminous coal is more than 59 per cent, it makes a coking coal; ratio between 55-59 per cent makes semi-coking and less than 55 per cent non-coking. Anthracite, although it has high carbon content and heating value, does not form a coking coal. Thus, volatile matter is also found to control the coking property. Coals with less than 17 per cent and more than 40 per cent volatile matters do not produce good coking coal.

Petroleum

Petroleum or crude oil is mainly hydrocarbon. The parent source of crude oil and the manner it was formed is the subject matter of great controversy and speculation but, it is largely believed to have been formed by the destruction of marine micro-organism, namely, plankton—meaning wanderers (to this class foraminifera and diatoms also belong). Planktons have been found to contain carbohydrate, protein and fat with minor

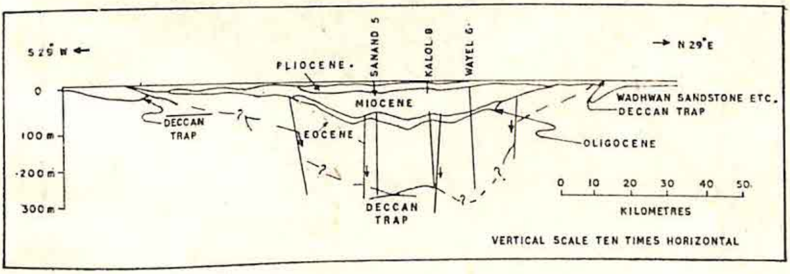


FIG. 9.1. Cross-section of the Cambay Basin *after* L.P. Mathur and P. Evans.

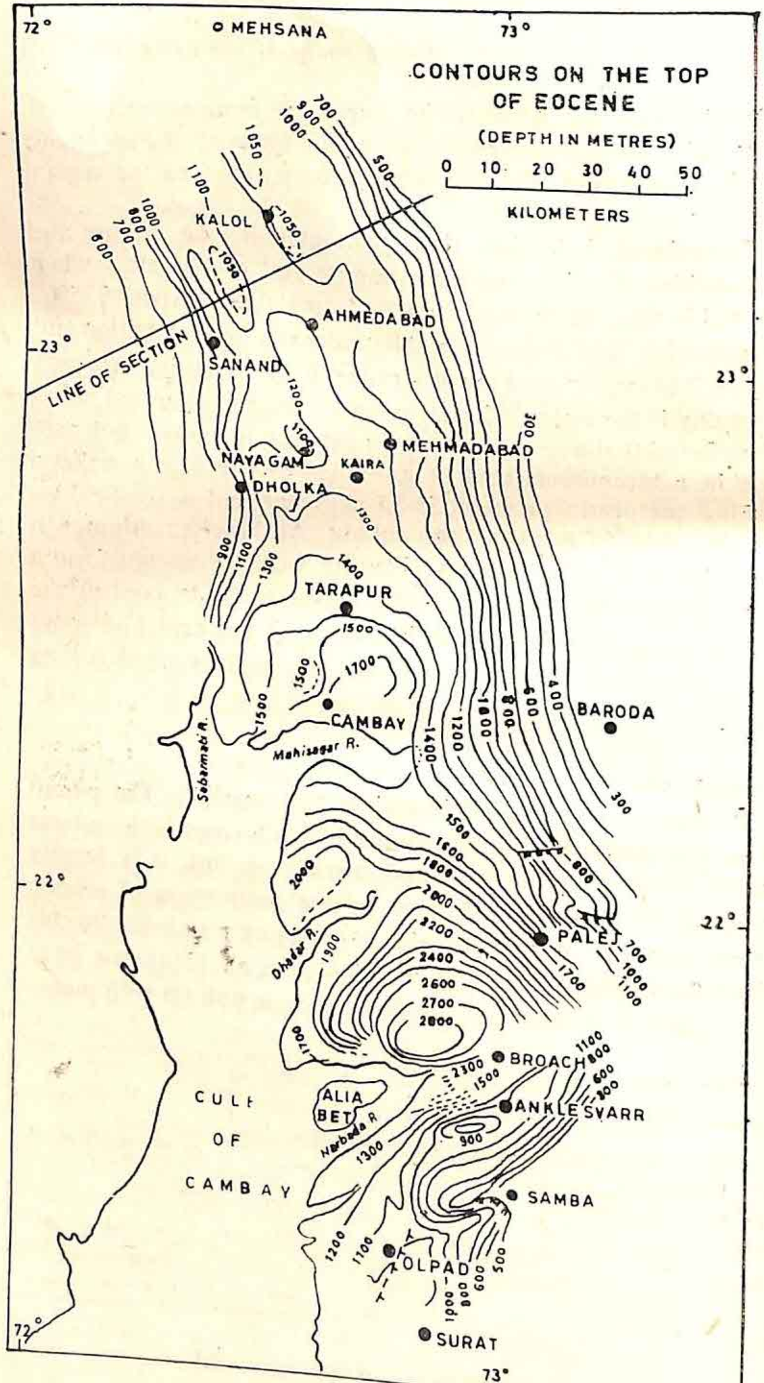


FIG. 9.2. Structural Map of Cambay Basin *after* L.P. Mathur and P. Evans.

quantities of hydrocarbons. On their decay, the hydrocarbons are distilled off and captured by porous formations like sandstone which keep it in trap. The carbohydrates also give rise to hydrocarbons with the loss of carbon dioxide.

$$\underset{\text{Carbohydrate}}{(CH_2O)_n} = xCO + \underset{\text{Hydrocarbon}}{yCH_2}$$

One striking point of crude oil is that it contains remarkable consistency in elementary composition. Generally, it has carbon content of 83-87 per cent; hydrogen 11-19 per cent and other elements mainly oxygen, nitrogen and sulphur up to 5 per cent maximum. Over 99 per cent crude oil consists of carbon and

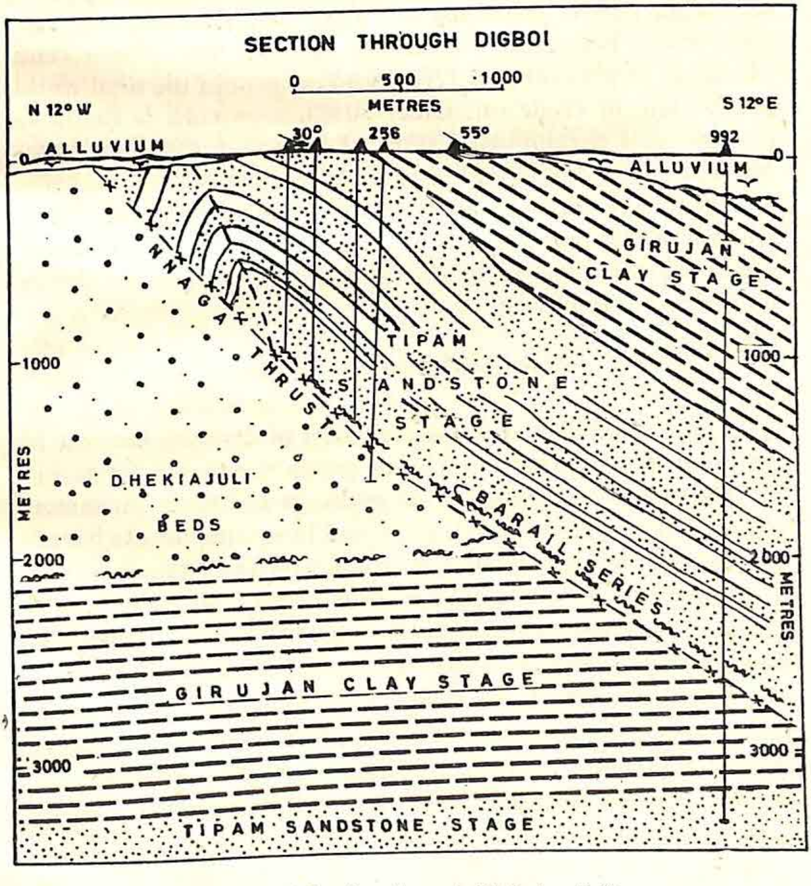


FIG. 9.3. A Section through Digboi anticline *after* L.P. Mathur and P. Evans.

hydrogen. The ash content is invariably low from 0.001-0.05 per cent. In contrast to simplicity of elementary composition, crude oil shows a great variability and complexity with respect to the compounds which may be present. It consists of variable mixture of three organic series:

(*a*) paraffins with general formula C_nH_{2n+2}

(*b*) naphthenes, ring type hydrocarbons with general formula C_nH_{2n};

(*c*) benzoid hydrocarbons with general formula C_nH_{2n-6}

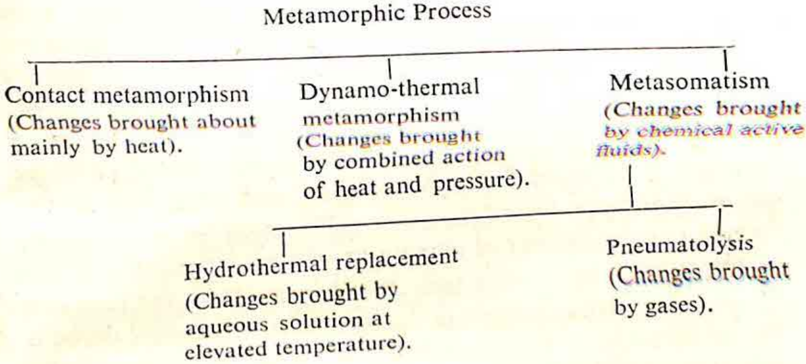
The proportions of these homologous series vary greatly from region to region and also in crudes originated during different geological periods. The petroleum is found to occur in porous sedimentary rocks belonging to Palaeozoic, Mesozoic and Tertiary eras. Palaeozoic formations account for 35 per cent; Mesozoic 15 per cent and Tertiary 50 per cent of the total world production of crude oil. Older strata, as a rule, is found to contain more paraffins than those of younger formations. Paraffin base oils are light and yield good lubricants, and asphaltic and naphthene base oils are heavy, unsuited for good lubricants, and are usable only for fuel oil. The hydrogen sulphide dissolved in the crude known as sour gas forms an important source for the recovery of sulphur.

METAMORPHIC PROCESS

As discussed in chapter 7, the sum total of changes brought in the pre-existing minerals or rocks, giving rise to the formation of altogether new minerals or rocks, is known as metamorphism. The processes which effect and bring significant changes can be described under three heads, as given in Table 9.1.

It should be remembered that from the purview of metamorphism, the changes brought out by the hydrostatic pressure of superimposed rocks and increase in temperature due to geothermal gradient at depth are excluded, as in the case of coalification. The subject-matter of metamorphism attracts the effect of heat and pressure and chemically active fluids, generated by tectonic movements and intrusion and extrusion of magma only. It is easily conceivable that when molten magma forces up it can produce three effects *i.e.* (*i*) produce heat, (*ii*) exert pressure, and (*iii*) release vast quantities of aqueous solution

TABLE 9.1


Metamorphic Process
Contact metamorphism (Changes brought about mainly by heat).
Dynamo-thermal metamorphism (Changes brought by combined action of heat and pressure).
Metasomatism (Changes brought by chemical active fluids).
Hydrothermal replacement (Changes brought by aqueous solution at elevated temperature).
Pneumatolysis (Changes brought by gases).

and gases; in addition to magmatic differentiation which will normally take place in the melt itself. The effect of heat produces marked changes at the contact zone especially when the country rocks belong to calcareous and argillaceous facies.

In fact, contact and dynamo-thermal metamorphism help in uniting mineral constituents of the pre-existing sediments to produce new and stable minerals suited to that particular condition. In such cases, new minerals formed do not tend to differ chemically from the original sediments or rocks, except that they become anhydrous. Many examples of minerals formed by contact and dynamothermal metamorphism have been described in the previous chapter. Graphite is the most common example of dynamothermal metamorphism where carbonaceous matter in the sedimentary rock and carbon of hydrothermal origin are transformed into graphite. Graphite is always found in metamorphosed rocks. The effect of heat and pressure even changes hematite-jasper ore bodies to magnetite-quartz ore bodies, as we find in Salem district in Tamil Nadu. The effect of heat, pressure or chemically active fluids cannot be considered in isolation, rather they invariably act simultaneously differing only in degree in relation to each other. Most significant changes are brought out by aqueous solution and gases at elevated temperature. Aqueous solution may carry mineral substances and while percolating through the surrounding rock, leave behind the solute in fissures, cracks, cavities and interstices of rocks invaded. Mineral deposits formed in this manner are put under *hydrothermal* of magmatic process. If the same magmatic solution reacts with minerals of surrounding mass to form minerals of different compositions, the process is then called hydrothermal replacement, replacement or most commonly metasomatism. The process of metasomatism, therefore, is not much different from the hydrothermal process, since the source of solution being the same, except that in the case of latter the minerals are formed from the original melt while the former brings alterations by addition or subtraction in the originally formed minerals either of igneous or sedimentary origin. Action of metasomatism is seen widespread in the field and is regarded as an important process in the formation of mineral deposits. The terminology like dolomitisation, serpentinisation, kaolinisation etc. often referred to under the subject of petrology and ore-genesis are the common processes of metasomatism. The formation of kaolin (china clay) offers one of the striking examples of metasomatism, where magmatic aqueous solution pervading through granitic country rock, reacts with felspar to form kaolin:

$$\underset{\text{Felspar}}{K_2O.Al_2O_3.6SiO_2} + 2H_2O = \underset{\text{Kaolin}}{Al_2O_3.2SiO_2.2H_2O} + K_2O + 4SiO_2$$

Most of the useful mineral deposits like asbestos, talc, magnesite, pyrophyllite, diaspore and many other minerals result from the process of metasomatism. Chrysotile asbestos largely results from the fibrisation of serpentine, which itself results from olivine, an important constituent of dunite, peridotite and picrite rocks.

$$\underset{\text{Olivine}}{5Mg_2SiO_4} + 4H_2O = \underset{\substack{\text{Serpentine or}\\ \text{chrysotile asbestos}}}{Mg_6Si_4O_{10}(OH)_8} + 4MgO + SiO_2$$

Serpentine has the same chemical composition as chrysotile but the latter is extremely fibrous where fibres can be taken out and woven like cotton thread. How the same olivine gives rise to serpentine and altogether new mineral chrysotile having fibrous structure is not yet known. In the same way the geochemistry of many minerals has not yet been understood perfectly. Only on the basis of their associations and modes of occurrence observed in the field, some conclusions are drawn regarding their modes of origin.

Talc $Mg_3Si_4O_{10}(OH)_2$ provides another interesting example.

It is found to be produced by the alteration of ultrabasics, dolomite and high magnesia limestone which have suffered a great deal of dynamothermal metamorphism. It is found that high quality talc is usually derived from sedimentary rocks. The talc originating from ultrabasic is rather impure and does not give that whiteness as given by talc formed from sedimentary rocks. Pyrophyllite $Al_2O_3.4SiO_2.H_2O$ has two modes of origin. It is found to result, from the alteration of acidic rocks like andesite, rhyolite tuffs, slate and schist in USA. In India, it is found at the contact zone of quartz reef with Bundelkhand granite in Uttar Pradesh and Madhya Pradesh. In Rajasthan, it is found at the contact zone of intrusive quartz veins and impure dolomite. In some places, diaspore $Al_2O_3.H_2O$ occurs at geodes parallel to quartz veins but never along with quartz as is the case of pyrophyllite. Magnesite $MgCO_3$ is found to be produced either as a replacement of calcium carbonate from dolomitic rock by magmatic solution or alteration of serpentine in ultrabasic rock. Both types of deposits are found widespread in the world.

In our country magnesite deposits formed by the replacement of dolomite are found at Almora in U.P. and that from alteration of serpentinous rock in Salem in Tamil Nadu and Dodkanya in Mysore district, Karnataka. Replacement deposits are usually crystalline in nature and that formed by the alteration of ultrabasic rocks are amorphous in character. Such observation is universal. The breakdown of serpentine releases silica forming opal and chalcedony around the magnesite mineralisation.

The realm of metasomatism is quite vast. Many more examples of metasomatism can be read in the textbooks of economic geology and ore-genesis. Sometimes, specific names are given to metasomatism depending upon the nature of changes brought in by different solutions, such as sulphur metasomatism, silica metasomatism and water and carbon dioxide metasomatism. Sulphur metasomatism can be illustrated by an example of pyritisation whereby iron pyrite is formed by the reaction of sulphide solution with iron in rocks. Phosphorus metasomatism is represented by the replacement of rocks by phosphate solution under the capping of guano—a phosphate bed formed from the secretion of sea birds. Widespread silicification of rocks by flint, chert, opal and chalcedony are the examples of silica metasomatism.

Pneumatolysis

The change effected by combined action of heat, water vapour, compounds of boron, phosphorus, fluorine, chlorine and other gases and the alkali metals in gaseous state is known as pneumatolysis. Many important minerals are formed by this process, such as muscovite, lepidolite (lithium mica), beryl, fluorite, topaz, tourmaline, axinite, apatite and scapolite. Pneumatolytic effects are more pronounced near intrusions of acidic magma than basic. It is evident that the type of minerals formed will depend upon the nature of gases evolved and the material with which they reacted. Acidic magmas give rise mostly to fluorine and boron in gaseous state. The boron vapours aid in the formation of tourmaline while reacting with biotite or felspar or with argillaceous sediments. The effect of tourmalinisation is regarded as the surest proof of pneumatolysis. The same boron vapour on reacting with calcareous sediments or basic rocks forms axinite, a boro-silicate of calcium and aluminium. The classical example of pneumatolysis is offered by tin deposits. Tin deposits are characterised by the presence of fluorite (calcium fluoride), topaz (fluoride and silicate of aluminium), wolfram (a tungstate of iron and manganese), ilmenite, tourmaline and various sulphides and arsenides of copper, iron, lead and silver. Cassiterite, an ore of tin, is supposed to have escaped initially in the form of SnF_4 from the magma and got deposited in fissures, cracks and in other suitable structures near intrusives; and later reacting with water vapour gave rise to the most common tin ore cassiterite, SnO_2.

$$SnF_4+2H_2O=SnO_2+4HF$$

The hydrogen fluoride evolved by this process is supposed to be responsible for the formation of fluorite and topaz on reacting with calcium and alkalies. The effect of chlorine pneumatolysis is also seen widespread, such as in the formation of veins of apatite $Ca_3(PO_4)_2CaCl_2$ and scapolite. Scapolite is largely produced by the introduction of chlorine in felspar. Introduction of wolfram, ilmenite, rutile, tourmaline, etc. in vein deposits of tin is regarded as the combined action of hydrothermal, and pneumatolysis metasomatism.

WEATHERING

Most rocks, after getting exposed to the atmosphere constantly for considerably long time, get disintegrated by oxidation, hydration and carbonation. The process of disintegration is known as weathering. Very few of us realise the importance of weathering in geological processes. It sets forth a change which becomes precursor to the formation of many economic mineral deposits. Initially, it breaks loose the rocks, dislodging mineral particles. This helps surface water to play its role in mechanically transporting the resistant minerals on carrying them away in solution which ultimately become sedimentary deposits of mechanical or chemical origin. One distinguishing class of deposit, namely, residual, is characteristic of weathering. As the name implies such deposits are the residual material left behind *in situ* after undesirable particles have been removed from the place. Bauxite deposit is the classical example which is formed by weathering of acid to basic rocks and schists, and subsequent removal of lime, alkalies, magnesium and iron compounds in solution, leaving behind hydrated alumina, containing some proportion of ferric oxide and other impurities like silica, ilmenite etc. In India, vast quantities of bauxite $Al_2O_3.2H_2O$ are found to occur as capping on Deccan trap in usual sequence from top to bottom as soil, murrum, laterite, bauxite, lithomarge, all resting on the original rock. Gibbsite $Al_2O_3.3H_2O$ and diaspore $Al_2O_3.H_2O$ also result from the same process and usually occur associated with bauxite. Lateritisation is the special name given to the process of weathering leading to the formation of bauxite. A distinction is made between laterite and bauxite by the presence of iron content. The residual altered rock mass is called laterite when the ferric oxide content is above 40 per cent; and bauxite when the same ferric oxide content is less than 40 per cent with a gradual improvement in alumina content. In bauxite, the alumina content tends to enrich to a little over 60 per cent. Lateritisation is a common feature of aluminium rich and iron rich rocks in tropical countries. Therefore, granite, gneisses and schists are prone to lateritisation. The effect of weathering is seen extending down to the depth of 30-40 metres deep. Weathering and consequential hydration give rise to clays and ochrous deposits. Garnierite, a most common nickel mineral resulting from the weathering of serpentinous rock, occurs as nickeliferous laterite. Deposits of china clay and manganese ore, at many places, are found as residual deposit.

SECONDARY SULPHIDE ENRICHMENT

It is an important phenomenon observed in sulphide ore bodies outcropping on the surface whereby the primary sulphide minerals of copper and to a lesser extent of lead and zinc ores, occurring in leaner proportion are enriched by the surface water and get concentrated and deposited above the water table as secondary sulphide, hydrated oxide and carbonate minerals of the same elements. The primary minerals break down to form sulphuric acid and soluble sulphate which, after getting activated by absorbing atmospheric carbon dioxide, dissolve the primary minerals and percolate down through the surface. In this manner, the soluble compounds are removed from the zone of weathering, leaving behind in most cases an impoverished residual material like limonite, psilomelane, hydrated silicate of magnesium and iron known as gossan indicative of the process. The percolating solutions under favourable condition precipitate out metallic compounds or the metals themselves, thus enriching the deposit at those levels. Precipitation takes place in proportion of relative insolubility of minerals in solution. It is observed that the upper zone above the water table gives rise to the formation of hydrated carbonate chloride, silicate and sulphate minerals like malachite $CuCO_3.Cu(OH)_2$, cuprite Cu_2O, chrysocolla $CuO.2H_2O,SiO_2$, atacamite $2CuCl_2.Cu(OH)_2$, azurite $2CuCO_3.Cu(OH)_2$; in the lower zone above the water table sulphide minerals like chalcocite Cu_2S, bornite Cu_5FeS_4, covellite CuS. The process of secondary enrichment in some cases is observed below the water level. It is mainly due to fluctuations in the water level.

10

Search for Minerals

Where to search and how to search are the two major problems towards the solution of which the entire knowledge gained in the various branches of geological science is applied in revealing horizons and areas for possible location of mineral deposits. The task is not as simple as it may appear to be; it requires a great deal of meticulous search and probe after taking into account all the geological features and facts to find out the localisation of mineral deposits. The science of geology has made it certain that if a geological map of an area with a correct record of geological setting is available, it is possible to indicate with precision, the likely occurrence of particular mineral deposits in that area. Such inferences are made out by studying the disposition of rock types which provides sufficient data to geologists to infer the possibilities of occurrence of specific minerals. Details regarding the shape and size, and whether the occurrence is of economic importance or not, are obtained by carrying out further prospecting work. Therefore, for obtaining a broad-based idea about mineral distribution of a country or of a particular area, it is necessary to have, or prepare a geological map showing the distribution of various rock types with their structural features.

A geological map is a record of geological facts. It is prepared on topographical maps invariably provided with physical features, like contours, location of villages, cities, roads, rivers and rails. For providing information about the geological settings on a regional scale, a topographical map usually of scale 1: 1,00,000 or 1″=one mile is selected. The geological settings as visible on the surface are recorded, and the distribution demarcated on the same. The visible feature like dip and strike of a bed if carefully shown would help in constructing the structure and stratigraphical sequence. A note describing the nature of rocks, signs of mineralisation etc. is made separately in a note book.

Mapping is done usually with the help of a plane table provided with a telescopic alidade. Initially, students are taught to handle Brunton compass and how to use it in the field for finding out dip and strike, and to determine their bearing on the map. Students will be able to understand details of the procedures only with practical experience when they go for field training during the course of their study. Mapping is a singularly great art and forms one of the most important aspects in geological science for unravelling the earth's crust and for locating deposits. When a topographical map of an area is not available, it becomes necessary for a geologist to prepare it himself with the help of a surveyor. On such a map, the geological facts are recorded as usual by making reconnaissance and traverses. It may be necessary to make a larger scale map, say of scale 1: 1000 of a mineralised area, so as to facilitate plotting all details visible on the surface. The choice of scale will depend upon the purpose to which the surface maps are required to be used and the area to be covered. The behaviour of veins and bedded mineral deposits is recorded separately in a note book for detailed examination and deciphering the possible extent of mineralisation underground.

Mineral deposits by and large are formed at depth below the surface but fortunately weathering and erosion make them to outcrop on the surface. This natural action of geological processes renders the searching mineral deposits a little easier. Outcrops are perceivable more in the case of sedimentary deposits than of igneous. In most cases, they remain buried. At some places, the signs of their occurrence may be found along nalla cuttings, gorges, banks of rivers and rivulets. These signs provide invaluable clues to prospectors. Such areas are selected for detailed prospecting for ascertaining the extent of mineralisation in aerial dimensions and in depth, and their economic viability. All such areas do not necessarily bear economic deposits. The experience in this regard is quite disappointing, especially in the case of mineral deposits of igneous origin. Prospecting records show a great variation from mineral to mineral and from deposit to deposit for the same mineral. In the case of non-ferrous metal deposits, only one out of 30-40 prospects may warrant exploitation, and if luck favours may back sufficiently to recoup the expenditure made on other abortive prospects. In most of the cases, the reserves proved are small or the grade too poor to be worked. It should be noted that in the case of mineral deposits of igneous origin, the deposits are most likely to be missed on preliminary prospecting as their concentrations may be low enough to escape visual inspection. In prospecting therefore, the principles of well-defined criteria and indicators are taken into account and form common guides.

PRE-REQUISITES TO PRELIMINARY PROSPECTING

Before going out for reconnaissance of an area, it is very necessary that a geologist and his associates acquire profound knowledge about the identification of common minerals and rocks during the course of their study. Each mineral and rock has specific physical and chemical properties by means of which they are identified. The physical properties include crystallography, form, colour (streak), hardness, cleavage, fracture, lustre, odour, feel, specific gravity, magnetic property, and radioactivity. The usually required material for field tests are carried in the field kit by a geologist when on a reconnaissance trip which must include all the time a geological hammer, pen-knife and a hand lens. Hematite ore can be identified in the field by the cherry red streak left on a streak plate, magnetite by its magnetic property, as it gets attracted to a magnet, limestone and dolomite by their strong and feeble effervescence on reaction with sulphuric or hydrochloric acid etc.; beryl and apatite often look identical in crystallographic form and colour, but they are easily distinguished from each other in hardness. The hardness of beryl is 8 whereas of apatite 5. Such minerals like chromite, asbestos, kyanite, diamond, and mica have a characteristic physical property by which they are readily recognised.

Some mineral occurrences which cannot be identified in the field are properly collected with identification marks superscribed on each of them, with a note on the location from where they have been collected, and taken to the laboratory for examination under petrological microscope, ore microscope, by chemical analysis and other advanced tests like X-ray and spectrograph. Most of the rock types can also be identified in the field by experienced geologists failing which the rock samples should be identified under microscope. How to identify minerals and rocks is taught in mineralogy and petrology and a geologist going for field work is supposed to be conversant with these subjects. Besides this, a geologist is also expected to have a field working knowledge about how to read and orient topographical maps, Brunton, clinometer, methods of plane table and theodolite surveying.

GUIDELINES TO PROSPECTING

The science of geology, as discussed in the preceding chapters, teaches us clearly that the formation of igneous, sedimentary and metamorphic mineral deposits takes place in different geological settings. The search for minerals of igneous origin is naturally required to be confined to an area of magmatic activities. Amongst these areas also, the distribution of acid, intermediate, basic and ultrabasic rocks should lead to search for only those minerals which are genetically associated with specific rock types as detailed in the previous chapter. For example, the search for chromite should only be confined to an area where an exposure of ultrabasic rocks is found. If the same rock type shows considerable alterations and visible fine cracks and fissures, then the area should also be searched for chrysotile asbestos, magnesite, and ochrous beds for garnierite. Again, if the same area has undergone metamorphic changes it should be prospected for minerals like soapstone and amphibole asbestos. Similarly, an area intruded by acidic rocks like granite should be searched for minerals of pegmatitic origin. Therefore, for making a field survey, two broad divisions should always be kept in mind about locating mineral deposits based on rock distributions; namely (*i*) areas covered by igneous rocks, and (*ii*) areas covered by sedimentary facies. Metamorphic minerals may be looked for in both types of areas wherever the changes stated above have taken place.

Climate, lithological facies, structure and geological time are the four important norms used in the search for minerals. A knowledge of climatic conditions is important for some minerals since they are formed under specific climatic conditions. Kaolinisation of felspar takes place mainly in a humid climate; deposits of evaporite class can be found only in an arid climate and laterite and bauxite in tropical climate. Coral limestone is found in areas of warm climate only. Placer deposits are also found in a humid climate. A study of lithological facies in relation to mineral formations is most important. The search for coal beds should confine to areas covered by Gondwana formations from Carboniferous to Jurassic period mainly. It is universal guideline. Lignite and coal are also found in Lower Tertiary formations such as in Tamil Nadu, Rajasthan, Gujarat and Assam. A significant guideline of lithological facies has been outlined in India for search of phosphorite deposits. In our country, phosphorite deposits have been found to occur in formations from Archaean to Tertiary eras. However, most economical deposits are confined to Archaeans. It has always been found that the presence of typical cherty black carbonaceous shale facies provides a positive clue to the occurrence of phosphorite with increasing prominence in the shaly facies, as the alkaline solution is more favourable for the precipitation of phosphates. Cratonic platforms and continental slopes up to 500 metre depths were the most favourable zones of phosphorite precipitation. Search for gypsum should normally confine to shallow basins of Mesozoic era and wherever marine transgression and regression have taken place. Amosite and crocidolite asbestos is always found associated with ironstones of pre-Cambrian sediments as we find in Bababudan hill of Karnataka and Transvaal of South Africa. This geological criterion is found universally true for locating these two varieties of asbestos. Similarly, it is seen that molybdenum has more affinity to alkaline rock like syenite than granite. The search for petroleum should invariably be confined to Tertiary formations although some sedimentary formations of Mesozoic and Upper Palaeozoic are also found to be petroliferous. For accumulation of petroleum, some definite structures are necessary such as domes and anticlines made up of porous beds like sandstone covered with impervious formations like clay and silt to prevent migration and evaporation. Lead-zinc deposits are invariably found to localise in calcareous country rocks of Pre-

Cambrian age. Calcareous rock is also a home of barytes and fluorite. Structural control is singularly important for study of localisation of mineral deposits. It has generally been observed that the major thrust planes are devoid of minerals and that the localisation takes place only in subsidiary fault planes and folds caused by the major thrust. Geological time also provides invaluable data on the occurrences of various minerals, for it has been found that the igneous activities of different ages have given rise to specific mineral deposits as it is found in the case of mercury deposits which are always associated with Tertiary intrusives, while the copper lodes of China are associated mainly with Cretaceous intrusive rocks. Salt domes of the USA intruding gypsiferous horizons are regarded invariably as of Tertiary era, and are an important source of native sulphur. Most of the world deposits of iron and manganese ores have been found to occur in Archean or Dharwar formations. An idea of studying world tectonics in relation to the distribution of minerals with age is gaining ground for a global search of mineral deposits.

GEOLOGICAL CRITERIA

During prospecting, thus, some well-defined geological criteria are taken into consideration and observed in the field. Definite repositories are known for minerals. They are found to localise and concentrate in areas of weaknesses like contact zones, cavities, fissures, cracks, bedding planes, folds, fault planes, brecciated zones, platforms, shallow basins, geosynclinal basins, areas of marine transgression and regression and areas of multiple igneous activities. They form principal areas where formation of mineral deposits takes place. Certain other geological indicators such as float ore, black sand occurring in the river bed or on the sea coast, wall rock alterations, gossan—oxidised and leached out outcrops--provide invaluable help in delineating areas of possible mineral occurrence. There are other methods for locating mineral deposits by studying anomalies provided by geophysical, radiometric and geochemical prospecting. These indirect methods have proved to be invaluable tools in the hands of geologists in locating mineral deposits. Of all the three indirect methods, the science of geochemistry and geochemical method of prospecting is advancing fast and has proved a most reliable method in locating hidden zones of mineralisation. Every year, new data are brought to light which have provided effective guidepaths in locating deposits in depth which otherwise could not have been located by mere ground surveys.

GEOPHYSICAL PROSPECTING

Under geophysical prospecting, generally four methods are adopted. These are: (*i*) magnetic; (*ii*) electrical; (*iii*) seismic, and (*iv*) gravimetric. Magnetic method is used to locate magnetic ore deposits like magnetite and pyrrhotite and to some extent cobalt ore. The influence of magnetic minerals on the earth's magnetic field is detected by a magnetometer and anomalies demarcated on the map. Magnetic effect due to pyrrhotite provides an inference of sulphide lodes like copper or nickel ores (where generally pyrrhotite is present). The magnetic method has also proved valuable in delineating contact zones between sedimentary rocks and basic igneous rocks. Basic igneous rocks always contain some proportion of magnetite which provide the anomalies between the two zones. The electrical method is applied for measuring the flow of current between an orebody when passed through two electrodes placed several metres apart. If the earth's composition is uniform, the flow of current will be uniform, and the fall in potential between the electrodes will also be uniform. But if areas between them have some mineral lodes which are either a good conductor of electricity or a non-conductor then the fluxes (flow of current) will tend to converge or diverge. The effect tends to increase or drop in potential in relation to normal drop which is measured by galvanometer placed at suitable distance between the two electrodes connected by wires. The anomalies, thus, indicate the possible zone of localisation of a mineral deposit. Mineral deposits of sulphides are good conductors of electricity whereas quartz reefs are non-conductors. The method has been successfully utilised in delineating the contours of a bed rock. Seismic method has been found more useful in prospecting of petroliferous beds and measuring thickness and depth of various sedimentary formations from reflection and refraction of artificially created earthquake waves. Gravimetric method is used to find out areas of high and low gravitational pull. By this method, the areas showing marked variations in the intensity of gravitational pull when compared to the mean earth's gravity are selected for further search. It is well-known that the heavier mass attracts plumb-bob while the lighter mass repels it. The areas which have been intruded by an igneous mass of basic character will have a greater intensity of attraction than those of sedimentary basins and igneous mass of acidic character. By deciphering zones of high and low intensity, areas are selected for possible occurrence of minerals genetic to such zones. Gravitational pull is measured by a Eötvös torsion balance. Geophysical anomalies are invariably required to be interpreted correctly from ground survey before test pits or drill holes are made to decipher them. In most of the cases, careful discrimination has to be made between infructuous and useful anomalies. Geophysical methods, however, narrow down the areas for search.

RADIOMETRIC METHOD

For prospecting of radioactive minerals like uranium, thorium, radium etc. which emit continuous gamma rays, a sensing device, Geiger counter, is used. It picks up gamma rays in its ionisation chamber and provides information by giving a particular sound. A considerable innovation has been made in the Geiger counter which now can also indicate the percentage of radioactive substances in the rock sample. A new instrument, beryllometer, has been invented for detecting beryl. Fluorescent lamp tubes are used in detecting fluorescent minerals like fluorspar, scheelite and even diamond. Radiometric method has its own limitations. It fails to pick up rays if the bed rock is below a one metre thick cover.

GEOCHEMICAL PROSPECTING

Geochemical prospecting is based on the theory that any element, if present in excess of quantity than required by a rock-type, will tend to migrate in ionic state. Almost all elements are found capable of migrating to various extent in some form or other, and get absorbed in the soil, covering the bed rock. Geochemical prospecting takes advantage of this property of an element. By analysing the soil sample for the presence of specific elements, an inference can be drawn about possible deposit. Geochemical results are checked and compared with normal background of the area. For example, an area is showing 80-90 parts per million of copper against normal background of 2-4 parts, it clearly indicates potential area for search. This method has been found to be most useful for tracing the presence of deposits of metals like copper, lead, zinc, tin, tungsten, antimony, gold, cobalt, molybdenum and even phosphates. The procedure of geochemical prospecting is simple and can be operated in the field. In one day, about 30 samples can be analysed by a team of two persons working eight hours. The operation of geochemical analysis is as follows:

Closely spaced soil samples are collected and sieved in a nylon sieve of 80 mesh. 0.1 gm of sieved sample is taken and dissolved in one part of nitric acid and three parts of water in a graduated long tube. It is then digested for an hour on a hot plate. The cooled material is made up to 10 cc with water. For testing copper, lead and zinc, 2 cc of the solution is taken. The solution is added to 10 cc of dithiozone reagent and shaken. A pink coloration is seen if either of the three elements are present. For testing the presence of elements separately, the control of pH of the solution is absolutely essential. Copper will provide pink coloration in dithiozone reagent only when the prepared sample solution is just acidic; lead will indicate its presence by pink coloration only at about 8.5 pH and zinc only in a natural solution. At the time of testing, pH of the solution is controlled and depressants are added to neutralise the possible effect of the other two elements. The process is repeated thrice taking 2 cc of the solution each time to find out the presence of copper, lead and zinc separately.

Dithiozone reagent is prepared by dissolving 0.01 gm of it in a litre of carbon tetrachloride and kept and carried in polythene bottles.

The amount of the elements present in a soil sample is measured by the depth of colour compared with a standard solution of copper, lead and zinc prepared specifically for this purpose. For testing the presence of phosphates, the usual procedure of sampling as detailed above is followed. The dissolved solution is tested in vanado-molybdate reagent (mixture of ammonium vanadate and ammonium molybdate). The presence of phosphorus gives a yellow coloration.

Similarly, different fluxes and digestion methods are adopted for testing the presence of other elements and the mineral formed thereof. By geochemical analysis, the presence of an element up to 0.1 per cent (1,000 parts per million) is tested. If the sample contains a higher percentage of an element, the usual quantitative method of analysis is followed.

Geochemical methods, therefore, provide near positive indications of the presence or absence of certain elements in an area and the minerals formed thereof by providing specific colour indications. Based on geochemical data, a geochemical map is prepared to delineate areas of possible mineral concentration. Very useful guidelines have been drawn which provide conclusive evidence for the presence or absence of deposits. For example, the distribution of lithium in granite and granodiorite rocks indicates the presence of tantalum veins. Rubidium and caesium show the presence of pigmatites. The presence of arsenic shows auriferous quartz. The presence of arsenic and antimony in the soil has led to the important discovery of lead-zinc ore bodies. Lead and molybdenum are the indicators of uranium minerals. Important information is conveyed by biotite, zircon, sphene and rutile which often carry increased concentrations of rare elements pointing to the possible occurrence of corresponding deposits in an area. Thus, the presence of tantalum and niobium in biotite derived from granite indicates some association with those granite and tantalum-niobium deposits, while the presence of tin in biotite indicates that the granite is stanniferous, lithium in quartz is an evidence of lithium-bearing quartz veins. The most recent discovery of geochemistry shows that the presence of tellurium provides a positive indication of deep-seated silver deposits. It has been observed that migration takes place from bed rocks seated as deep as 300-400 metres from the surface.

PHOTOGEOLOGY AND REMOTE SENSING

Aerial photography is an advance method of geological studies including mineral exploration. This branch of geology is known as photogeology in which aerial photographs are used to interpret geologic details. This process is adopted generally for a terrain which is not easily accessible by ground. It provides a great help in the preparation of a base map with speed and economy. Nowadays, a recourse to photo-geology has become a common method for quick appraisal of the areas. Aerial photographs are taken with the help of a camera fitted with aircraft and held vertically directed towards the ground. The photographs are usually taken from a height of 2,000 m to 10,000 m or so depending upon the scale of photography that is desired. The scale of the photograph is the function of the flying height and also the focal length of the camera used. The aircraft is made to fly at a fixed altitude on a grid pattern, equally spaced with a fixed speed having automatic device for taking photographs at regular intervals. In such photographs overlapping does take place. Normally, 60 per cent forward overlap and 20 per cent sidelap is maintained. This provides an excellent stereoscopic coverage. By combining the two adjoining photographs, 60 per cent common area under a mirror stereoscope, a three dimensional model of the terrain is created. This provides a bird's eye view of a large area from which morphological features, rock formations and structural features can clearly be identified. It is now possible to identify the rock types by studying the photograph characters such as tone, texture, pattern and similar other associated features. From the photographs, it is possible to make lithological and stratigraphical interpretations and selecting zones for further search which can be reached by means of a helicopter. These days, aircraft is fitted with all arrangements of making simultaneously magnetic, gravimetric, and radiometric observations while taking aerial photographs. In an open and well exposed country with moderate to low relief 1:50,000 scale or 1:40,000 scale photographs can be used for reconnaissance survey and 1:15,000 to 1:30,000 scale photographs for detailed mapping.

A tremendous advance has been made in obtaining earth's data by remote sensing devices. Nowadays artificial satellites are made to rotate round the earth on an altitude of approximately 900 km above the surface for monitoring and relaying to the earth varieties of data like geological features, anomalies, environmental conditions and more so keeping surveillance over a wide range of activities on the surface. The concept of obtaining data through satellite was first mooted by Dr William Fischer of NASA during the sixties. He conceived the idea of Earth Resources Technology Satellite (ERTS) which was later renamed as LANDSAT satellite to distinguish it from SEASAT. The satellites are provided with a combination of sensor and relay system. The remote sensing is defined as acquisition of data without being in physical contact with the object of study. Landsat is usually provided with an imaging instrument called the Multispectral Scanner (MSS) and the Return Beam Vidicon (RBV) like television camera system that records landscape brightness in three wave length bands, data collection system (DCS), receiver and transmitter and wide band video tape recorders. The DCS has been used to monitor volcanoes and hydrological phenomenon. It is only by the help of satellite, it was possible to forecast imminent danger of sea flooding coastal regions of Andhra Pradesh during the successive years of 1977 and 1978. The photographs related by the Landsat satellite, known as 'Landsat imagery', provide an excellent panoramic view of the geological relief covering vast areas. Such photographs provide an ideal information on geological features such as natural drainage system and lineaments that are necessarily required for a project like connecting Ganga-Kaveri basin.

Landsat satellite is generally launched into a near-polar orbit (see Fig. 10.1). The orbit of satellites are sun-synchronous to ensure repeatable sun illumination conditions. The speed of the satellite is such that it crosses the equator in every 103 minutes; during this time the earth rotates a distance of 2,767 km under the satellite at the equator. In 18 days, one satellite obtains coverages of nearly the entire earth surface. The infra-red including invisible thermal infra-red photography helps the satellite to obtain pictures in all atmospheric conditions throughout day and night.

In India, the task of aerial photographs are executed by Indian Air Force and the photographs can be obtained from the office of the Survey of India. Near Hyderabad, there is an earth station set up by National Remote Sensing Agency which receives the data from the orbitting satellites such as Landsat. Remote sensing technology is now widely used in geology more so in understanding geomorphology, forestry, agriculture and

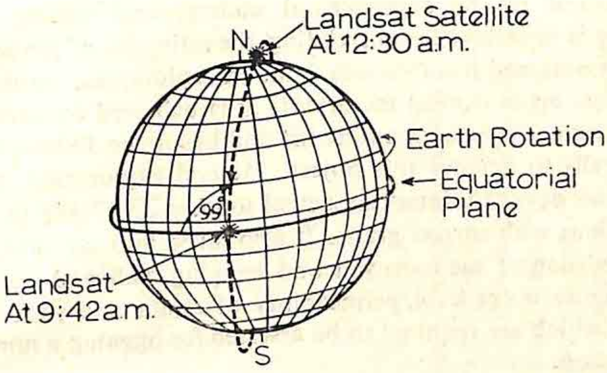


FIG. 10.1

land use survey and for monitoring environmental pollution, movement of the glacials and such other activities.

PROSPECTING AND EXPLORING

The object of prospecting is to find out mineral shows and decipher them one by one for possible exploration by assembling all the data gathered by different methods of survey. As all mineral shows do not necessarily result in paying prospects, the aim of prospecting is mainly directed towards finding out which of the shows have signs of economic importance. For this, a limited amount of pitting, trenching as well as drilling may be necessary for ascertaining the extent of mineralisation as well as grade. If the preliminary data provide encouraging results, the same prospect is subjected to detailed prospecting, namely, exploration. The main object of exploration is to obtain a three dimensional picture of a deposit to determine its quantitative and qualitative features. This helps in studying economic viabilities from the mining and investment point of view. The method and evaluation of exploration depend upon the type of deposit and the nature of mineralisation. In the case of bedded deposits, making pits at regular intervals or drilling at intervals of 300-500 metres apart may be regarded to be adequate. In the case of vein deposits, especially for non-ferrous deposits, drilling may be spaced at maximum intervals of 50-100 metres. In these cases, the drilling data are required to be checked up by experimental underground mining. This measure is necessary for correlating the estimates of grade and reserves obtained from surface data. In exploration, estimation of correct grade is most important. It is achieved by sampling which itself is a great scientific art and has to be followed systematically to achieve this object. Mineral exploration, therefore, aims at ascertaining the actual tonnage available in fixed dimensions with correct grade. It also takes into consideration the condition of the foot-wall and hanging wall and the roof in the mine, water level, permeability of strata and such other factors which are required to be assessed for opening a mine for production.

Appendix I

List of Common Economic Minerals and Their Modes of Occurrence

MINERALS OF IGNEOUS ORIGIN

Mineral	*Composition*	*Modes of Occurrence*
Apatite	$3Ca_3(PO_4)_2.CaCl_2$ or $3Ca_3(PO_4)_2.CaF_2$	Mostly occurs as apatite magnetite veinde posits associated with basic intrusive rocks containing pyroxenites. It is found disseminated in all types of igneous rocks, mostly alkaline in nature such as apatite-nepheline deposit of USSR.
Anatase and Rutile	TiO_2	As accessory minerals in granite and granodiorite. Placer deposits as beach sands always form the commercial source.

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Arsenopyrite	FeAsS	Occurs in quartz-veins and acid intrusions.
Baddeleyite	ZrO_2	Found in phonolite rock. Commercial source are from alluvial pebbles.
Barytes	$BaSO_4$	Hydrothermal deposits, forming veins, fissure filling and replacement. Solution responsible for the formation of barytes is genetically related to basic intrusive magmas.
Beryl	$BeO.Al_2O_3.\ 6SiO_2$	It occurs in pegmatites.
Bismuthinite	Bi_2S_3	It is an ore of bismuth. Bismuth also occurs in native state. Bismuth ore is never independently mined, mostly recovered as co-product during refining of lead. It occurs in association with copper, lead, silver and tin deposits.
Cassiterite	SnO_2	It is the chief ore of tin. It is of pneumatolytic origin. Veins of cassiterite is usually found to contain topaz, fluorite and wolfram. Occurs as disseminated crystals in granite. Chiefly obtained from placer deposits.
Chromite	$Cr_2O_3.\ FeO$	Always associated with ultrabasic rocks like peridotite, serpentinite, dunite, picrite, saxonite etc.

		Occurs as lenses, patches and disseminated deposits.
Chrysoberyl	$BeO. Al_2O_3$	Although silica devoid mineral, but occurs in pegmatites.
Cinnabar	HgS	An ore of mercury. Cinnabar may occur in any rock which has been fractured thus making ingress of solution. It is always associated with Tertiary volcanoes of acidic rocks, formed as hydrothermal deposit at low temperatures as at Almaden, Spain; fissure veins at Monte Amiata in Italy; breccia filling at Idria, Italy; and as stock-works, pore-filling and hair cracks.
Cobaltite	$CoAsS_2$	Occurs with copper sulphides.
Columbite	$(Fe, Mn). (Nb, Ta)_2O_6$	In pegmatites.
Copper ores:		Copper sulphide ores are found associated with tongues of acid granites to intermediate intrusives. Native copper is found as hydrothermal filling crack, amygdales and forming partial replacement in basic lava flows. Copper sulphides usually contain recoverable percentage at one stage or other of their treatment, of following metals:
Chalcocite	Cu_2S	
Chalcopyrite	$CuFeS_2$	
Bornite	Cu_5FeS_5	
Covellite	CuS	
Cubanite	$Cu_2SFe_4S_5$	

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
		gold, silver, platinum, bismuth, nickel, selenium and cobalt.
Corundum	Al_2O_3	In syenite rock.
Diamond	C	In kimberlite rock and its extrusive. Occurs as disseminated crystals of varying sizes.
Enangite	Cu_3AsS_4	Copper-arsenic mineral, occurs in quartz rich veins.
Fluorite	CaF_2	Formed by pneumatolytic actions.
Galena	PbS	Chief ore of lead. Found associated with granitic rock intruding carbonate country rocks. Usually occurs in association with sphalerite, a zinc ore, like co-brothers, often contains copper and silver in workable quantity. Lead-zinc mineralisation is chiefly formed by hydrothermal solutions as fissure fillings. In lead-zinc deposits, it is always observed that the formation of pyrite mineralisation takes first, followed by pyrrhotite sphalerite and galena.
Gallium	Ga	Element gallium is found in minute quantities associated with copper and zinc ores. Also found in coal ashes.

Garnierite	$H_2(Ni, Mg)SiO_4$	It is an important ore of nickel. Always associated with basic rocks, such as peridotite, serpentinite. It is found to occur as lateritic nickel resulting from the weathering of serpentinous rocks etc.
Germanium ores:		
Germanite	$Cu_3(Fe, Ge)S$	Germanium ores are never independently mined. Usually obtained from zinc slimes.
Argyrodite	$4Ag_2S.GeS_2$	Found in association with silver deposits.
Gold	Au	It is always associated with acid rocks from Pre-Cambrian to Tertiary age. It is found as fine dissemination in blue quartz of granites. Also occurs with copper sulphide ores and as gold-telluride.
Ilmenite	$FeO.TiO_2$	An important source of titanium metal, usually occurs in basic rocks chiefly with anorthosite forming veins and as segregation with magnetite and vanadium mineral roscoelite. Also occurs as ilmenite-hematite as in Allard lake, Canada and ilmenite-norite rocks in Norway. Beach sands form an important source of ilmenite all the world over.
Indium	In	Usually found in zinc slimes.

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Lithium minerals:		
Amblygonite	$LiAl(F,OH)PO_4$	In pegmatites, sometimes caesium minerals are associated with lithium ores.
Lepidolite	$K_2Li_4Al_2F_4Si_8O_2$	
Petalite	$Li(Al, Si_4)O)_{10}$	
Spodumene	$Li(Al(SiO_3)_2$	
Lithiophilite	$Li(Mn, Fe)PO_4$	
Triphylite	$Li(Fe, Mn)PO_4$	
Magnetite	Fe_3O_4	Large deposit is found in association with gabbro and anorthosite. As an accessory mineral, it is found in all rocks.
Molybdenite	MoS_2	Usually associated with granite, granodiorite, monzonite in minute disseminations as found in Henderson mine of Climax Molybdenum Co. and Questa mine of Molybdenum Corpn. of America, USA, and Endako mine of Endako Mines Ltd., Canada. It is also obtained as co-product during the refining of copper ores as in Chile.
Monazite	$(Ce, La, Yt)PO_4$ with ThO_2	Occurs as accessory mineral in granites and pegmatites. Placer deposits are the chief commercial source.
Muscovite	$(H, K)AlSiO_4$	Found in pegmatites intruding mica schist coun-

(Ruby mica)		try. Pegmatites occur as dykes, sheet, pipes and irregular masses.
Niccolite	$Ni.As$	Occurs in acid rocks, usually associated with sulphide veins of copper ores.
Orthoclase	$K_2O.Al_2O_3.6SiO_2$	Chief constituent of granite. Occurs in pegmatites and veins forming chiefly of felspar containing subordinate proportion of quartz.
Orpiment and Realgar	As_2S_3 AsS	These occur as a minor constituent in the veins of silver, gold and lead ores. Also found in association with antimony ores.
Pentlandite	(Fe, Ni)S	Commonly occur intergrown with pyrite, pyrrhotite, millerite (NiS) and niccolite (NiAs) in copper sulphides vein originating from acid igneous rocks.
Pollucite	$2Cs_2O.2Al_2O_3.9SiO_2.H_2O$	It is a caesium ore. Occurs in association with lithium mineral petalite.
Platinum	Pt	Usually associated with basic and ultrabasic rocks. Also occurs as mineral sperrylite ($PtAS_2$) in association with copper-nickel sulphides as is found in Rustenburg and multimetal lodes in Sudbury.
Pitchblende	$2UO_3.UO_2$	It is an important uranium mineral, usually found associated with acid to intermediate intrusive rocks. It occurs in fissure veins formed by hydrothermal process. Most commonly found in

Appendix I (*Contd*)

Mineral	*Composition*	*Modes of Occurrence*
		association with cobalt, nickel and copper ores and mineral monazite. Seventeen uranium minerals are known. Only 0.8 per cent of uranium in rock makes it economically workable.
Pyrite and Pyrrhotite	FeS Fe_nS_{n+1}	Found in all types of rock. May occur as massive bodies as if of magmatic segregation. Mode of origin is difficult to interpret. Commonly found in association with all sulphide ores.
Quartz	SiO_2	Main constituent of acid rock. It may occur independently as vein quartz or quartz forming reefs.
Rhenium	Rh	It occurs in minute quantities, usually obtained from molybdenite roast flue dust.
Rutile	TiO_2	It occurs as accessory mineral in acidic rocks. Commercial source of rutile is beach sands.
Samarskite	Complex composition containing U, Nb and Ta.	In pegmatites.
Selenium	Se	Usually recovered from the copper slimes.
Silver minerals:		
Native silver	Ag	There are eight minerals of silver recorded so far. Out of which argentite is the most important. It is found associated with granodio-
Argentite	Ag_2S	

		rite and phonotite rocks. Chiefly occurs with gold, lead, zinc and copper mineralisations, where it may occur as solid solutions.
Stibnite	Sb_2S_3	It is the chief mineral of antimony. It occurs as vein deposit of hydrothermal origin associated with quartz as in Bolivia. Also found to occur in association with lead-zinc ores.
Sulphur	S	Native sulphur has two modes of origin, one volcanic and other chemical. Volcanic deposits are mined chiefly in Italy and Japan. Salt domes found in Louisiana and Texas are regarded to be of chemical origin. Sour gas (H_2S) associated with crude petroleum is now finding a major source of sulphur.
Topaz	$(Al,F)_2SiO_4$	Found in granite and pegmatites originated by pneumatolysis.
Tungsten minerals:		
Wolfram	$(Fe,Mn)\ WO_4$	Found in pegmatitic veins, often associated with quartz-gold veins.
Scheelite	$CaWO_4$	
Uranite	$Ca(UO_2)P_2O_8.8HO_2$	Most commonly associated with granite and syenite rocks.
Vanadium minerals:		
Carnotite	$K_2O.2U_2O_3.V_2O_5.2H_2O$	Patronite is found in association with nickel and molybdenum sulphides, roscoelite occur in peg-

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Patronite	VS_4	matite and is formed by replacement of aluminium of muscovite; and vanadinite is found to occur in the oxidation zone of lead ores. Carnotite besides forming source of vanadium and uranium is also a source of radium. It is found to occur as seams and pockets in sandstones in Colorado.
Roscoellite	Vanadium mica	
Vanadinite	$Pb_5(VO_4)_2Cl$	Twenty vanadium minerals are recorded so far but none of them forms independent source of vanadium. The paragenesis of vanadium minerals is not fully understood. It is found to occur in association with basic to acidic rocks in combination with aluminium, calcium, copper, lead, uranium, bismuth and sulphur. The most common source of vanadium is vanadium bearing titaniferous magnetitic ores. Coal ash in several places in the world is found to contain appreciable amount of vanadium. Such ash forms important source chiefly in USA. Crude oil of Venezuela and Mexico is high in vanadium, and it is recovered from soots that collect in the boilers and

		stacks of ships burning Venezuelan and Mexican oil. Certain Peruvian asphalts yield more than 30 per cent V_2O_5 from their ash. At Mina Ragra in Peru, which is the chief source of vanadium in the world, it is recovered from black carbonaceous rocks containing 10-13 per cent V. Several laterites contain appreciable amount of vanadium.
Zircon	$ZrSiO_4$	It is a common accessory mineral of granite, syenite and diorite. Its commercial source is beach deposits only.

MINERALS OF CHEMICAL ORIGIN

Anhydrite	$CaSO_4$	Occurs as evaporites associated with gypsum. It precipitates out in sea water at about 25°C.
Boron minerals:		
Boracite	$7B_2O_3.5MgO.MgCl_2$	Boron minerals are generally found in dried up shallow lakes or basins called 'playas' of Tertiary age. Sassoline and borax are also found around volcanic vents and in spring waters.
Borax	$Na_2O.2B_2O_3.10H_2O$	
Colemanite	$2CaO.3B_2O_3.5H_2O$	
Kernite	$Na_2O.2B_2O_3.4H_2O$	
Sassoline	H_3BO_3	
Ulexite	$Na_2O.2CaO.5B_2O_3.16H_2O$	

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Brucite	$Mg(OH)_2$	It is formed by hydration of periclase (MgO) and occurs in association with magnesite, dolomite etc.
Calcite	$CaCO_3$	It is crystalline variety of limestone and forms vein deposits by infiltration of lime solution.
Celestite	$SrSO_4$	In evaporites associated with rock salt, gypsum and clay. In salt domes it occurs as geodes in limestone. It is found filling the cracks and spaces within phosphatic nodules in Tiruchirapally.
Chalcedony	$SiO_2.nH_2O$	Chalcedony is cryptocrystalline variety of silica and is regarded to have formed by precipitation of silica in colloidal solution. There are several varieties of chalcedony depending upon colour and bands, namely, agate, onyx, sardonyx, carnelian, bloodstone, jasper, flint and chert etc. They mostly occur as amygdales *i.e.* filling the vesicles and cavities of lava flows.
Clay Minerals:		
Ball clay	$Al_2O_3.2SiO_2.2H_2O$	Occur as bedded deposits.
Bentonite	$(OH_4)\ Si_8Al_4O_{20}.nH_2O$	Bentonite is regarded to have been formed by the

China clay	$Al_2O_3.2SiO_2.2H_2O$	alteration of volcanic ash of Upper Cretaceous and Fuller's earth represent a shaly facie of Tertiary age. Ballclay, china clay and fire-clay have more or less same chemical composition but differing in physical properties.
Fire clay	$Al_2O_3.2SiO_2.2H_2O$	
Fuller's earth	$(OH_4)\ Si_8Al_4O_{20}.nH_2O$	
Dolomite	$CaCO_3.MgCO_3$	By direct precipitation or by replacement of limestone by magnesium solution. The process is known as dolomitisation.
Epsomite	$MgSO_4.7H_2O$	Occurs as evaporites.
Gypsum and Selenite	$CaSO_4.2H_2O$	Occurs as evaporites. Selenite is crystalline variety of gypsum.
Hematite	Fe_2O_3	It is chief ore of iron. It is found occurring as a thick bed alternating with jasperite in geosynclinal beds.
Kankar	$CaCO_3$ Mixed with clay	It is formed by desiccation of lime solution coming up to the surface by capillary action.
Limonite	$2Fe_2O_3.3H_2O$	It is generally found in swampy area and in gossan zone and regarded to have been formed by hydration of hematite and siderite.
Limestone	$CaCO_3$	Formed by chemical precipitation.
Manganese minerals:		
Braunite	$3Mn_2O_3.MnSiO_3$	Manganese minerals are generally found occurring in metamorphosed sediments of Archaean age, forming thick lenticular masses. It is also
Manganite	$Mn_2O_3.H_2O$	

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Psilomelane	$MnO_2.H_2O$	found to occur as a bedded deposit along with hematite as in Orissa. The source rocks from which manganese sediments, later transformed into minerals, were derived is still a matter of great speculation. There are about 137 minerals of manganese known, all of them are found in metamorphosed sediments. In Tirodi, Balaghat distt., the country rock is granite and gneisses which contain richly spessartite (manganese-garnet) along with other garnets. It is inferred that spessartite might be the one source of manganese sediments.
Pyrolusite	MnO_2	
Rhodochrosite	$MnCO_3$	
Rhodonite	$MnSiO_3$	
Sitaparite	$9Mn_2O_3.4Fe_2O_3.MNO_2.3CaO$	
Phosphorite or rock phosphate	$Ca_3(PO_4)_2$ Composition variable.	Occurs as bedded and disseminated deposits and found to occur in all ages. It is formed by reaction of phosphoric solution in sea water with limestone.
Potassium minerals		
Alunite	$KAl_2(SO_4)_2(OH)_6$	Potassium minerals are very soluble in water. They are formed by evaporation of saline lakes and basins in dry regions.
Carnallite	$KCl.MgCl_2.6H_2O$	
Kainite	$KCl.MgSO_4.3H_2O$	
Nitre	KNO_3	

Polyhalite	$K_2SO_4.MgSO_4.2CaSO_4.2H_2O$	
Sylvite	KCl	
Pyrite	FeS	It may occur as bedded deposit as found at Amjhore in Bihar and also as infiltration in veins. Pyrite is readily formed by the action of sulphurous solution with iron minerals.
Sodium minerals:		
Galuberite	$Na_2SO_4.CaSO_4$	Sodium minerals are very soluble in water. Occur as evaporites in regions which receive scanty rainfall.
Mirabilite	$Na_2SO_4.10H_2O$	
Natron	$Na_2CO_3.10H_2O$	
Rock salt	$NaCl$	
Thenardite	Na_2SO_4	
Trona	$Na_2CO_3.NaHCO_3.2H_2O$	

MINERALS FORMED BY ORGANIC PROCESS

Diatomite	Primarily silica with minor alumina	Diatomite occur as thin to thick beds measuring up to 300 m from the accumulation of skeletons or frustules formed as a protective covering by diatoms—single celled microscopic plants. Marine deposits belong mainly to Miocene or Pliocene age. Fresh water deposits may be of Pleistocene or Recent age, Kieselguhr is the other name of diatomite.

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Limestone: Coral Foraminiferal Limestone etc.	Nearly pure $CaCO_3$	Coral forms atolls and reefs on the ocean floor. Foraminifera, molluscs, crinoids, bryozoa and other calcareous shell invertebrate like gastropods have given rise to many partially consolidated to unconsolidated beds analysing nearly pure calcium carbonate. They form thick bedded deposits.
Guano	Calcium phosphate	It is one of the important sources of phosphorous rock. It is formed by secretion of sea birds. Thick deposits of guano are found in several islands in Pacific Ocean.

MINERALS FORMED BY METAMORPHIC PROCESS OTHER THAN METASOMATISM

Aluminium silicates: Andalusite Kyanite Sillimanite	$Al_2O_3.SiO_2$	Always found associated with argillaceous schistose rocks forming massive masses.
Graphite	C	Flake graphite occurs as disseminated, patchy masses in metamorphosed sedimentary rocks such as gneiss, schists and marbles, formed from the carbonaceous matter deposited with the sediments. Amorphous graphite forms bedded depo-

		sits resulting from the metamorphism of coal.
Marble	Essentially $CaCO_3$	It is formed by recrystallisation of limestone. Marble may be formed from the recrystallisation of many rocks, providing pleasing colour on polish.
Phlogopite	$H_2KMg_3Al(SiO_4)_3$	It is found associated with pyroxenites. Occurs in book-form.
Wollastonite	$CaSiO_3$	It is the product of contact metamorphism of siliceous limestone.

MINERALS FORMED BY METASOMATISM

Asbestos		A group of fibrous minerals are named asbestos. They occur as crossfibre, slipfibre or massfibre forming veins and veinlets in the parent rocks at the contact zones. Chrysotile, which is the principal variety of asbestos, always results from olivine to serpentine with fibrous structure. In Cuddapah, it is found occurring at the contact zone between Vempalle dolomitic limestone and olivine rich basalt sills.
Amosite	$(Fe,Mg)SiO_3.1\text{-}5H_2O$	Amosite and crocidolite occur as fibrous vein at the contact zone between ironstone and jasper.
Anthophyllite	$Mg_7Si_8O_{22}(OH)_2$	

Appendix I (*Contd.*)

Mineral	*Composition*	*Modes of Occurrence*
Crocidolite Chrysotile Tremolite	$NaFe(SiO_3)_2.FeSiO_3.H_2O$ $3MgO.2SiO_2.2H_2O$ $Ca_2Mg_5Si_8O_{22}(OH)_2$	Other varieties result from varied and complex processes and found occurring in metamorphosed derivatives of amphibolites, pyroxenites and other plutonic ultrabasic and basic rocks, and sometime in crystalline limestone.
China clay	$Al_2O_3.2SiO_3.2H_2O$	Results from the alteration of felspar of granite and gneisses. This alteration may be caused by two processes: (*i*) by the action of ordinary surface water of felspar: or (*ii*) by the action of superheated magmatic waters.
Magnesite	$MgCO_3$	Occurs as massive veins formed in the dolomitic country and ultrabasic plutonic and dunite. It is formed by removal of lime in dolomite and replacement of silica from serpentine by hydrothermal carbonate solutions.
Pyrophyllite	$Al_2O_3.4SiO_2.H_2O$	It is found to occur at the contact zone between the quartz reef intrusive and the granitic country rock.
Soapstone or Talc	$3MgO.4SiO_2.H_2O$	It forms massive bodies and is derived from dolo-

		mite and basic plutonic rocks which have suffered regional metamorphism.

MINERALS FORMED BY ALTERATION AND WEATHERING

Bauxite	$Al_2O_3.2H_2O$	They usually occur as capping on the hill tops. Bauxite etc. is the main product of lateritisation of alumina rich rocks. The process takes place in tropical climate mainly.
Diaspore	$Al_2O_3.H_2O$	
Gibbsite	$Al_2O_3.3H_2O$	
Garnierite	$(Mg.Ni)O.SiO_4.H_2O$	Garnierite can be called nickeliferous serpentine. It occurs as residual concentration as nickeliferous silicate from weathering of serpentine.
Limonite	$2Fe_2O_3.3H_2O$	Forms from the weathering and hydration of siderite, hematite, magnetite etc. Limonite is the typical mineral show of gossan zone.
Ochre	Hydrated ferric oxides	Decomposition products of ferruginous minerals present in various rock types and occur as small pockets and irregular bodies. As residual deposits, formed by removal of soluble ingredients of rocks and minerals.

MINERALS FORMED BY THE PROCESS OF SECONDARY SULPHIDE ENRICHMENT

(See page 110)

Appendix II

Specific Uses of Metals and Minerals

METAL

Aluminium: It is one of the lightest metals having specific gravity 2.7; it can be drawn into wire and rolled. It makes strong alloys. It is finding expanding use in the manufacture of body of high speed cars, aeroplanes and space aircraft; bars, windows, decorative panels in sophisticated buildings; household utensils; and most revolutionary use is in the electrical transmission lines where it has replaced copper. Although its conductivity is 30 per cent less than copper but owing to its lightness for weight it is regarded superior to copper in transmission lines. Aluminium has to a great extent replaced tin in containers, packing foils and tubes; brass and bronze in utensils. Aluminium powder is used as paint.

Antimony: Antimony alloys due to their property of expanding on cooling, reproduce fine details of the mould and hence used for type metal. Antimony imparts hardness and mechanical strength to lead. Antimonial lead is employed as an antifriction metal, shrapnel ball in bullet core, storage battery; and in telegraphy. Lead alloys contain 1 to 25 per cent antimony. It forms several important alloys with other non-ferrous metals.

Arsenic: It has limited use. In fact its presence is considered harmful in alloys. Small quantities of arsenic is, however, found to increase resistance of heat and corrosion properties in copper; therefore, arsenical copper is used in motor car radiators, calico-printing rollers.

Beryllium: It is a coveted white metal much lighter (specific gravity 1.85) than aluminium and far stronger in tensile strength. It forms a strong alloy with only 2.5 per cent addition with copper and becomes as hard as steel. Copper-beryllium

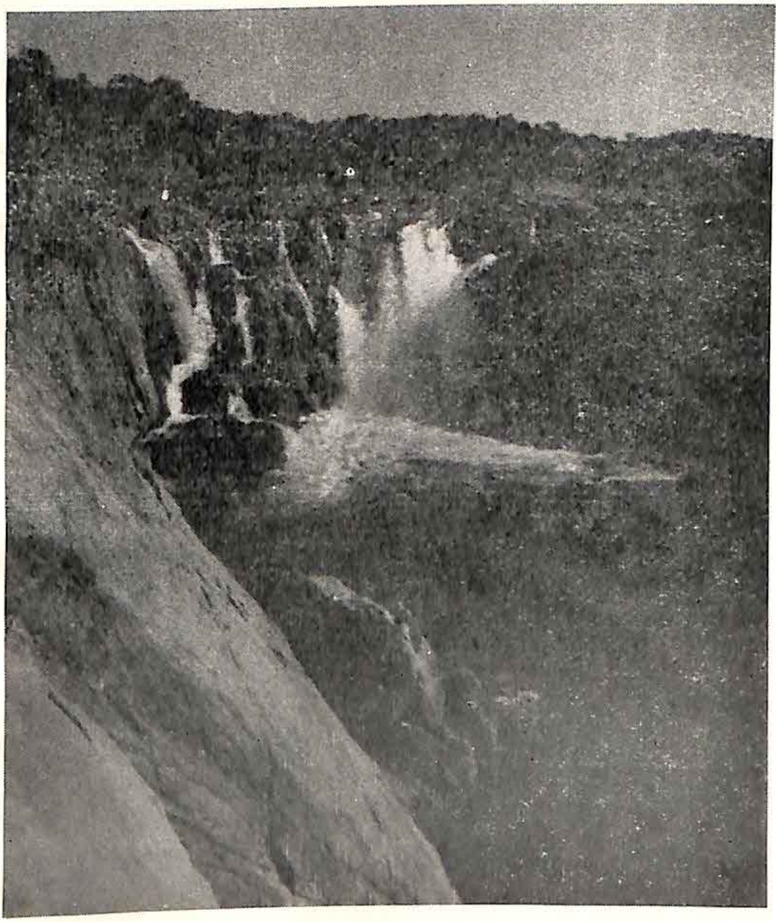
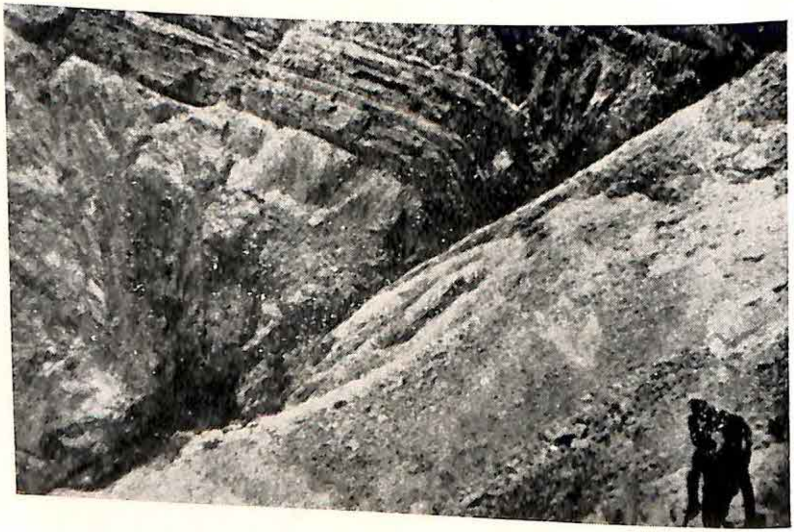


Plate 1. View of a water fall. (Although water falls are a source of water and electricity at the same time they are first class landscapers.)

Plate 2. A view of hanging glaciers Central Himalaya. Glaciers are also natural landscapers (Photo Courtesy: GSI).

Plate 3. A view of a fault (Geological Survey of India, Memoir xxiii).



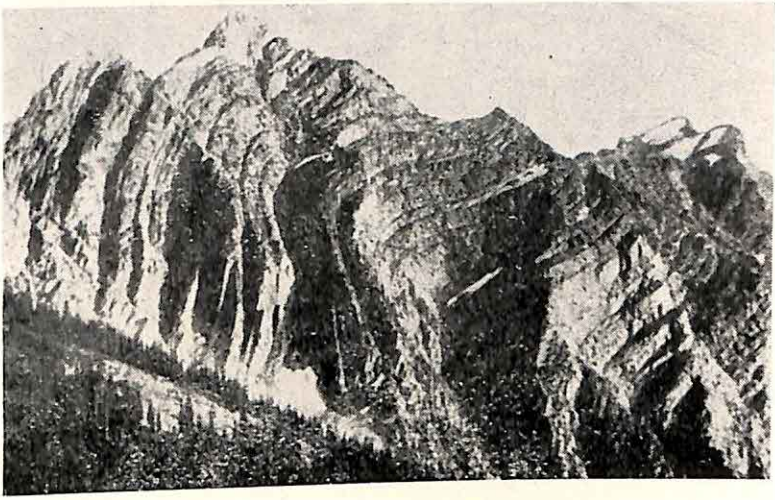
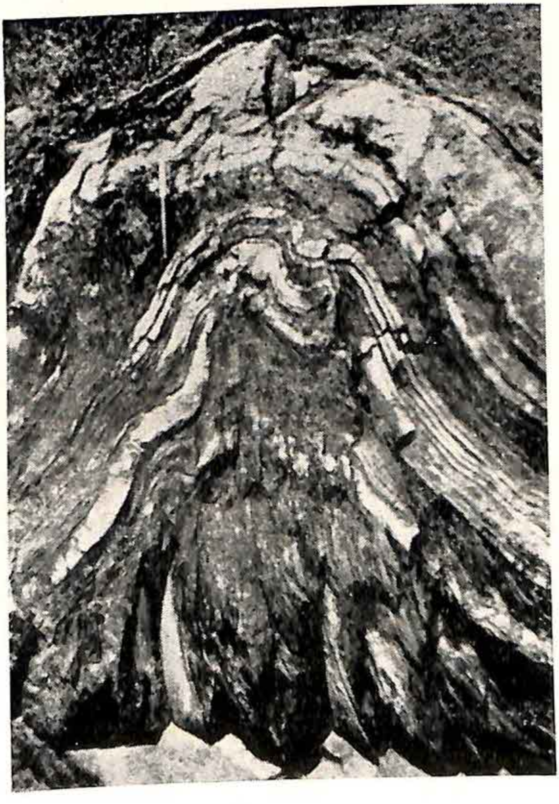


Plate. 4 A view of a fold (Courtesy: United States Geological Survey).

Plate 5. View of a fold.



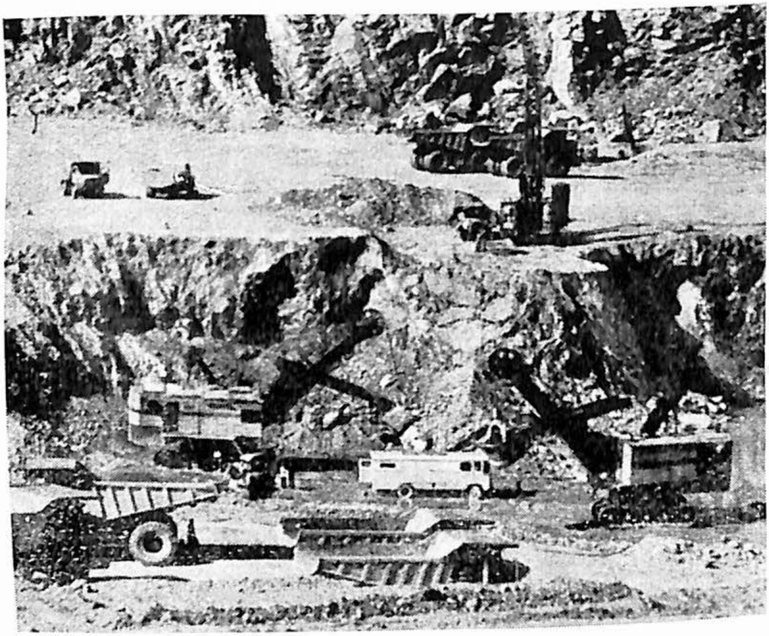


Plate 6. An open-pit mine.

Plate 7. An open-pit mine of iron ore.

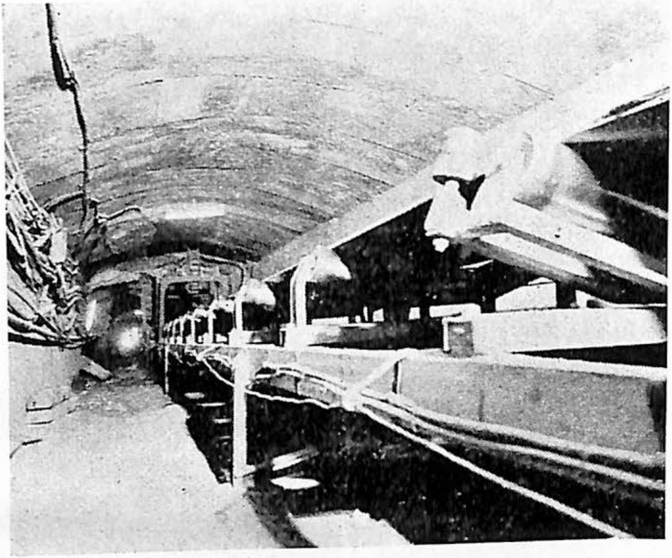


Plate 8. A view of underground mining.

Plate 9. Underground mining.

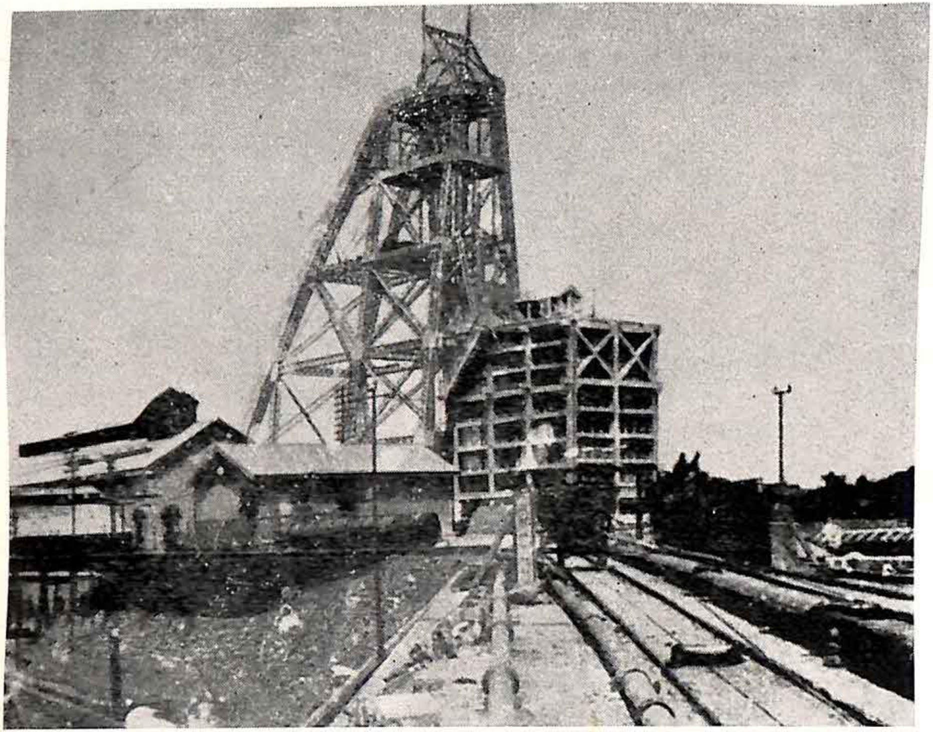


Plate 10. A view of a shaft. It is a means to haul ore from underground and also to transport workers inside the deep mine.

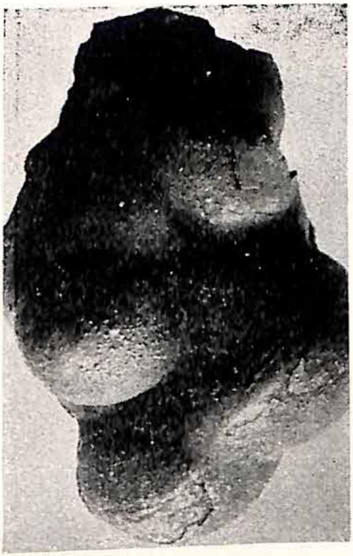
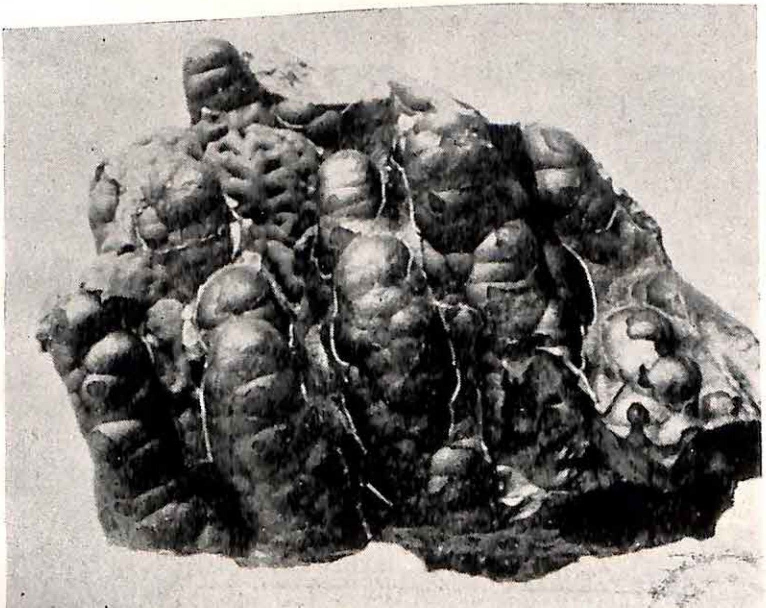


Plate 11. Botroydal structure in a manganese ore. (From Raikora Mine. Bunches like these hang down in the cavities in the manganese bed.)

Plate 12. Stalactitic structure in a manganese ore (from Kalaparbat Mine).



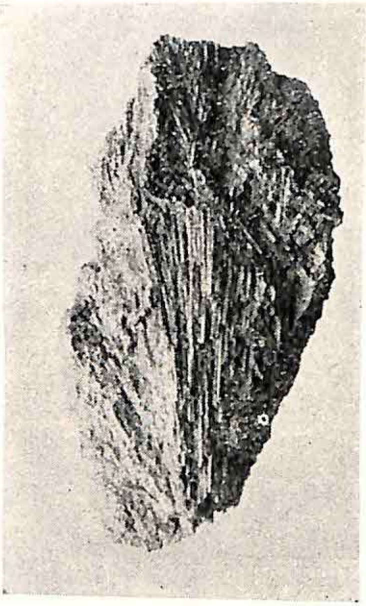
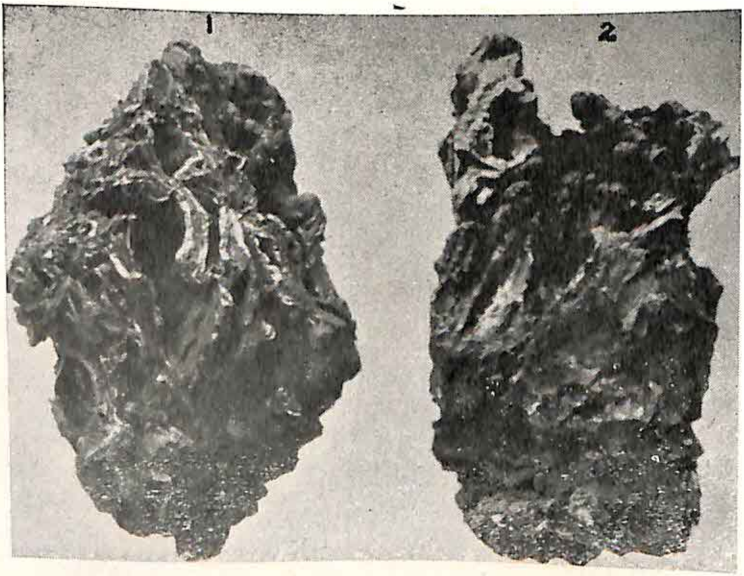


Plate 13. Needle structure in a manganese ore (from Kuttingi Mines):

Plate 14. (1) Box structure in a maganese ore,
(2) Cavities in the ore are filled with velvety stuff (chemical grade manganese dioxide).
(from Mahasukha Mines.)



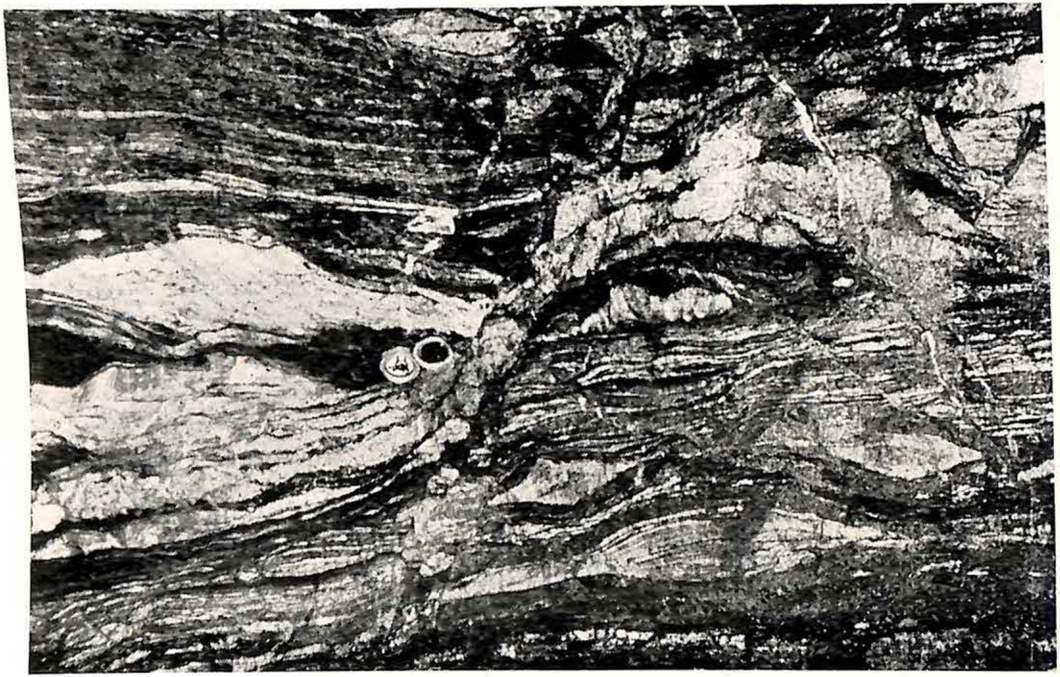


Plate 15. View of the fault line.

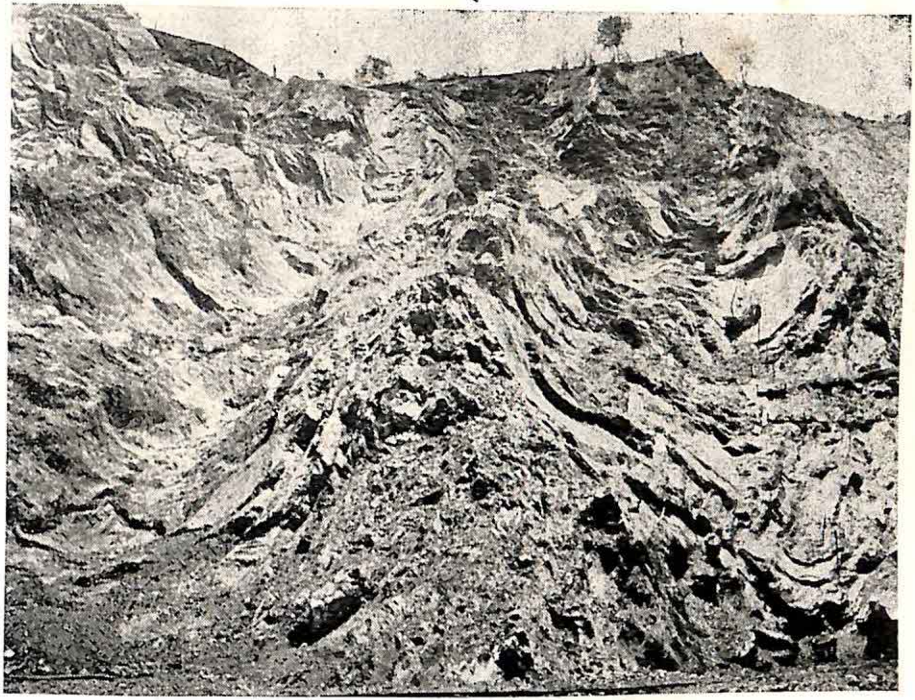


Plate 16. A result of erosion and denudation.

alloy is non-sparking and non-magnetic and thus finds expanding use in aircraft, space craft, switches, engines and motors. Beryllium oxide is employed as a source of neutrons along with radium for the bombardment and splitting of uranium atoms and for slowing down the high speed fission neutrons emitted from uranium in order to control the chain reaction involved in the explosion of an atom bomb. Beryllium oxide is an excellent high temperature refractory and finds use in electrical furnaces and in the manufacture of aircraft spark plugs.

Bismuth: Bismuth finds use as its compounds in medicinal and cosmetic preparations. Bismuth forms fusible alloys with lead, tin, cadmium, and antimony which are employed as automatic fire extinguishers, fuses for hand grenades. Bismuth amalgam is used for silvering mirrors and interiors of vacuum tubes. Bismuth antimony alloys are used for type metals.

Caesium: Finds use in photoelectric cells which are used for taking picture, television and automatic door opening.

Cadmium: It is used in the processing of uranium and in the manufacture of special steel. It imparts excellent resistance to corrosion actions. Copper cadmium alloys are used in electrical transmission wire. Cadmium nickel alloys are used in storage batteries. Cadmium sulphide is a good pigment which imparts golden yellow colour. Cadmium is employed in reactors to control fissionable elements.

Cerium: It is used in the form of ferro-cerium alloy which is a brittle metal and when abraded emits sparks like flint. It is for this purpose used in cigarette lighters.

Chromium: Largest use of chromium is in the production of chromium steels, where it is used in the form of ferro-chrome. Commercial ferro-chromes contain 65-70 per cent chromium. Chrome metal is used in the electroplating. It forms important alloys with nickel, cobalt and tungsten and used in the manufacture of resistant wires for heaters. Chromium in the form of ferrochrome is used in the manufacture of stainless steel and tool steel and heat resistant steel. Stainless steel contains about 18 per cent tool steel up to 1.5 per cent and heat resistant steel as much as 25-35 per cent chromium. Chromium steel are highly resistant to chemicals.

Cobalt: Cobalt imparts special characteristics in steel. Cobalt steel is employed in the manufacture of jet aircraft engines, gas turbines, turbo super chargers and high speed tools. It improves magnetic qualities in iron and hence used in the electronic industry for producing permanent magnet. Manufacture of permanent magnet is the largest single use of cobalt without which there could be no communication system required in radio, television and many other electronic devices.

Copper: Copper is an excellent conductor of electricity next in superiority to silver only. It is a basic metal of electric energy. It can be drawn into wire easily. Copper wire is used in the winding of motors' armature. In the building and household purposes, this metal is used as wire, pipe and sheets. Brass (copper and zinc alloys) and bronze (copper, zinc and tin alloys) are the two important alloys of copper in which form it finds extensive use.

Gallium: Gallium is liquid like mercury at low temperature and hence also used in thermometry.

Germanium: It is the principal material for semiconductor. This metal has led to the invention of transistorised devices. Germanium has replaced valves of radio sets in transistor.

Gold and *Silver*: Gold and silver are chiefly used as jewellery.

Indium: Finds use in dental metal alloys; imparts amber colour to glass.

Lead: Finds use largely as alloys, chiefly solder-type metal and bearing metal, plumbing pipes and storage batteries.

Magnesium: Next to beryllium, it is the lightest metal known which finds large commercial applications. A plane built from magnesium alloys weighs one-third less than when built from aluminium alloys of the same strength. Magnesium metal is used as incendiary bomb for flares.

Mercury: Principal use of mercury is in electrical apparatus for making electrical contacts and in thermometers. It finds large use as a chemical as well.

Molybdenum: It has properties equal to tungsten and forms a good substitute of tungsten in all uses. Only 25 per cent of it makes the alloy steel very hard.

Nickel: It is used in electroplating; forms an important alloy such as monel metal (63-69 per cent nickel, 29-32 per cent copper and about 3 per cent iron), German silver or nickel silver (10-30 per cent nickel, 40-70 per cent copper, 1-9 per cent zinc), nickel bronze (75 per cent nickel and 25 per cent copper).

Nickel and chromium are the major partners in the manufacture of stainless steel. For heat corrosion application nickel steel has no substitute. Over four-fifth of nickel production in the world goes to alloy steels, especially armour for warships, tanks etc.

Platinum: Nearly 50 per cent of its production is utilised in jewellery and dentistry. The most impressive advance in the use of platinum is in catalytic plant in oil refining to yield a higher grade petrol. The platinum catalyst has been found to raise octane ratings by 300 per cent. It has excellent anti-corrosive property because of this it is used for lining pressure vessels in chemical industry. Another best known use of platinum is in thermocouples, providing an accurate measurement up to 1700°C. Electrical contacts and laboratory crucibles are other important uses. Practically all high quality optical glass, camera lenses and colour television tubes are created in platinum crucibles. When alloyed with a little iridium or ruthenium, it becomes one of the hardest metals in existence. Applied to razor blades and surgical instruments, it provides the sharpest and most durable cutting edges ever developed. In pure form it is very malleable and ductile. A 100 gm piece can be rolled into a sheet 0.09 mm thick, broad enough to cover a tennis court, or drawn into a 117 km filament of almost invisible fineness. Dies made of platinum are used for extruding glass fibre, rayon and such other substance.

Rhenium: Used for planting tungsten which imparts long life. Pen nibs are often coated with rhenium.

Selenium: Its main use is as a semiconductor. Also used in making colourless glass by neutralising the effect of iron, in television, in xerography, in a.c. rectifiers, in rubber industry and as an additive to steel and other important alloys.

Tantalum and *Columbium*: Mainly used in vacuum tubes for their great affinity for gases.

Tellurium: It is a semi metal used for making tough hard rubber and colouring glass.

Tin: Largely used for plating of steel sheets for making tin cans. Tin has antitoxic property and thus tin cans are extensively used for packing eatables. Tin and lead alloys are used for soldering electrical wires.

Titanium: Titanium metal is slightly heavier than magnesium and aluminium but retains strength at temperature as high as 800°F and consequently gains priority for use in the fabrication of airframes, rockets and turbojets.

Tungsten: In the form of ferro-tungsten, it is used in the manufacture of steel for high speed cutting tools, armour plates. Tungsten is strongest and most refractory metal having melting point of 6150°F and hence tungsten steels are used in the manufacture of equipments which operate at high temperature. High speed tools contain as much as 18 per cent tungsten. As tungsten carbide, it forms important material in the manufacture of metal cutting tools and drilling bit. Tungsten has remarkable ductability; 10 kg can be drawn into wire of 4 km in length. Because of its refractoriness and ductability it finds application as filament in the electric bulbs. Less than 1 tonne of tungsten metal can produce filament for making 100 million bulbs.

Thorium: Thorium isotope Th_{233} is fissionable and used as atomic fuel. It is produced by neutron bombardment of the natural thorium Th_{233} which gets transmuted into uranium isotope U_{235} (Thorium Th_{233} or U_{233} is the same) after emitting two electrons. Natural thorium metal finds use in the manufacture of gas mantle.

Uranium: Uranium is a metal which is obtained from mineral pitchblende and uranite. Natural uranium U_{238} has a most common isotope, U_{235}. It is most powerful radioactive substance which continuously emits sub-atomic particles from its unstable nucleus. The emission of radioactive particles produces energy. It is observed and found that if the nucleus of a uranium atom is broken by artificial means such as by bombarding with neutron from an external source, it produces tremendous amount of heat. This heat can be harnessed in producing nuclear energy in atomic reactor. When U_{235} nucleus splits in a natural way, the spare neutrons are thrown out at a terrific speed of some 10,000 miles per second. At this speed they have practically no chance of striking another nucleus of U_{235} for causing fission. Generally these high speed neutrons recoil and so their chances of causing fission in another nucleus become remote. But if their speed is slowed down by means of a suitable moderator such as graphite, beryllium oxide or heavy water to a speed of about 1 mile per second (it is called thermal speed) then the chances of causing fission in another U_{235} nucleus become very high, because slow neutrons are greatly attracted to U_{235} nucleus. And by this way, a sustained chain reaction is caused and maintained in a nuclear reactor.

Vanadium: It is used in the form of ferro-vanadium to impart toughness and heat treating characters in the steel. Vanadium steels are used for making spring, tools, high speed parts and permanent magnet. Vanadium pentoxide is used as catalyst in sulphuric acid manufacture.

Zinc: It finds largest use as galvanising material for protecting steel tubs, buckets and wires from atmospheric corrosion. Die-casting, brass, outer shell of dry battery cells and rolled products are the other four important industries where zinc metal finds use.

Zirconium: Pure zirconium is resistant to heat and corrosion. It is completely incapable of capturing thermal neutrons: it has, therefore, attained importance in the manufacture of structural and cladding material in atomic reactors. Zirconium forms alloys with steel, silicon and tungsten. Nickel-zircon-steel possesses the same property as tungsten with steel and, therefore, it has a special significance to the countries deficient in tungsten. Zirconium metal is used on electronic tubes and flash light bulbs.

MINERAL

Apatite, phosphorite or *rock phosphate*: A source of phosphorus, which is the main plant food. Nearly 90 per cent production of rock phosphate is used in the manufacture of phosphate fertiliser, remaining 10 per cent for the extraction of element phosphorus and various phosphatic chemicals.

Asbestos: Chrysotile, crocidolite and amosite varieties among asbestos minerals find commercial use, of which first one is most important. Asbestos mineral consist of delicate fibres like cotton thread but in tensile strength it is stronger than steel for the same diameter of asbestos fibre. It has a unique property of resisting fire and acid and is non-conductor of heat and electricity. It can absorb cement 20 times of its volume and forms well cemented mass like reinforced cement concrete. These properties are utilised for making asbestos cloth, rope, cord etc. Short fibres are used for asbestos mill board, asbestos cement sheets, asbestos rubber sheets etc.

Barytes: Barytes is the main source for barium chemicals like barium chloride, carbonate and blancfixe. In pulverised form, it is used as an extender in paints, and in the preparation of drilling mud.

Bauxite and *Gibbsite*: They are important source of aluminium ore. High grade bauxite and gibbsite containing low percentage of silica and iron are used in the manufacture of alum and refractories. Diaspore, a monohydrate variety of bauxite is used largely as a refractory material and forms a good substitute of kyanite.

Borax and *Other Borates*: Borax is used for the manufacture of boric acid, an antiseptic solution. Borax is largely used in the preparation of soaps, cosmetics, insecticides, germicides, fungicides, disinfectants, medicines and food preservations. Boro-silicate glass acquires good property of thermal shocks and hence largely used for laboratory glasses. Other borates are converted into borax before they find use.

Calcite: It is mostly used as a filler in rubber goods. It forms an ingredient in the manufacture of spark plugs and ceramic material. Transparent variety of calcite, known as icelandspark, is used in the manufacture of nicol prism for petrological microscope.

Chromite: It is a common ore for the manufacture of ferrochrome and chromium metal. Chromite is also extensively utilised in the manufacture of refractory bricks required in steel metallurgy and in the production of chromium chemicals like potassium and sodium dichromates.

Ball clay, *Bentonite*, *China clay*, *Fireclay* and *Fuller's earth*: China clay and ball clay are the important ingredients of porcelain wares, spark plugs. China clay is extensively utilised as a loading material in high class paper and textile. Special quality of China clay is used in the manufacture of antiseptic lotions. Bentonite is used in the preparation of drilling mud for its thixotrophy property. It also finds large use as a moulding material. Fireclay is mostly used in the manufacture of fireclay refractory bricks. Fuller's earth is used in the refining of petroleum and vegetable oils.

Coal and *Lignite*: They are one of the principal source of heat and power. Coking coal on carbonisation gives rise to coke and several by-products like tar, ammonia, benzole, heavy and light naptha, xylene, toluene, benzene, light oil—xylenols, cresols, phenol; carbolic acid—cresylic and creosole; creosote oil—heavy creosote, anthracene oil, phenanthene, carbazole etc.

Corundum: Corundum is the hardest mineral next only to diamond and hence extensively used as abrasive material. The crystalline and transparent variety of corundum is valued as a high class gem stone. Ruby is the name given for a scarlet red, sapphire for bluish colour transparent crystals of corundum.

Diamond: Diamond is divided into two groups: (*i*) gem variety which is crystalline and (*ii*) industrial variety which is crypto-crystalline. Crystalline variety is mainly used for making gems and crypto-crystalline as cutting tools. Diamond is hardest substance known on the earth and can even cut steel easily. Selected crystals of diamond are used for making diamond dies for drawing copper, tungsten wires etc.

Diatomite: It is a first class filter aid material for trapping undesirable substance in colloidal form and hence it is used in filtering medicinal chemicals, syrups etc.

Dolomite: Dolomite after calcination is used in the manufacture of refractory bricks, largely used in iron and steel industry. It is also used as fluxing material along with limestone in blast furnace. Dolomite containing less than 0.5 per cent iron is used in the manufacture of colourless glass. It is an important source of magnesium metal.

Fluorspar: It is a principal source of fluorine and fluorine chemicals and synthetic cryolite which is indispensable to aluminium extraction. Fluorspar in small quantity at the rate of 1 kg per tonne is used as fluxing material in steel metallurgy. In glass industry it is used for making opalescent glass.

Felspar: It (chiefly potassium felspar and to a lesser extent sodium felspar) forms an important ingredient of ceramic and glass mixtures.

Graphite: Crystalline graphite of about 70 per cent purity is used in foundry facing to prevent adherence of castings. It is extensively used in the manufacture of crucibles. Softness and flaky nature of graphite is taken advantage of in making, with addition to oil, a good lubricant for heavy duty machinery operating at high temperature. Amorphous graphite bounded with clay make the 'lead' of the pencil. Manufactured graphite has now replaced several uses of natural graphite like electrodes, dynamo-brushes and lubricants. Pure graphite is used as moderator in the atomic reactor.

Gypsum: Finds main use in the manufacture of cement, aluminium sulphate fertiliser, plaster of Paris and distemper. In fertiliser it forms a source of sulphate. High grade gypsum is used in the manufacture of plaster of Paris and distemper. In cement industry it is added as a retarding agent. Only 5 per cent addition by weight to the clinker of cement makes the cement settle slowly, thus prevent cracking effect when set.

Ilmenite and *Rutile*: These are the chief sources of titanium metal and titanium dioxide paint. Rutile is also extensively used in the manufacture of arc welding electrodes.

Iron ore: Hematite and magnetite are the chief iron ores used in the manufacture of iron and steel. Spathic iron ore is used for generation of hydrogen from steam. Bog iron ore is used for separating hydrogen sulphide from municipal gas supply.

Kyanite, *Sillimanite*, and *Andalusite:* These three alumino silicate minerals are largely used in the manufacture of mullite bricks.

Limestone: It finds multifarious uses depending upon grade. Mainly used in the manufacture of cement, as fluxing material for iron and steel and other metallurgical industry, in the production of precipitated calcium carbonate, bleaching powder, calcium carbide etc. As lime, it is used in clarification of cane juice, whitewashes etc.

Magnesite: Magnesite is largely used for making refactory bricks after dead burning. Such bricks are mainly used in iron and steel industry. Caustic burnt (containing 2-7 per cent CO_2) magnesite is used in making sorel cement which is employed for flooring deck of the ship and as chemical accelerator in the manufacture of synthetic rubber. Epsom salt is manufactured by digesting magnesite with sulphuric acid. Magnesite is also a source of magnesium metal.

Manganese ore: Manganese ores are chiefly utilised in the manufacture of ferro-manganese which is a must in steel production. Ferro-manganese helps in removing sulphur from steel melt.

Muscovite and *Phlogopite mica:* Muscovite is first class electrical insulator and is valued for its dielectric property *viz*.

power to withstand high voltage and extremely low power loss factor. Phlogopite finds the same use as that of muscovite but its dielectric property is inferior to muscovite. Mica is used in different forms, in almost all the sophisticated electrical instruments like radio, T.V. sets and electrical gadgets.

Ochres: They are naturally occurring colouring agents and used in the manufacture of primers mainly.

Pyrophyllite: It is most effective substitute of talc although it has got different chemical composition. It is used for the same purpose where talc is used.

Quartz and *Silica sand:* Mainly used in the manufacture of glass. Graded sand particles are also used in the manufacture of abrasive sand-papers.

Sulphur: Principal use of sulphur is in the manufacture of sulphuric acid in which form it is used in host of industries. Sulphur dioxide gas is used in clarification of sugar juice.

Talc, *Soapstone* or *Steatite:* Talc finds multifarious use. It is a softest mineral known and largely used in making face and body talcum powder, as a filler and loading material in paper, plastic, linoleum and rubber goods. Steatite blocks are used as lining in alkali tank, table tops as it resists acid and heat actions. Talc is practically non-conductor of electricity and for the reason of its easy cutting into different shapes and sizes is used as insulator in electrical switches. It forms an important ingredient in ceramic material required in the manufacture of different components for radio and T.V. sets. Low grade talc powder is a first class disinfectant.

Vermiculite: Vermiculite has got a peculiar property of expanding several times its original volume when heated. Vermiculite in expanded form is used in the manufacture of light weight insulating bricks for thermal and accoustic insulation. A new property of retaining sub-surface water has been noted in vermiculite. This property can suitably be tested after mixing it with fertiliser and adding to such soil where porosity is high.

Wollastonite: It is a new mineral of which different uses are being experimented. Experiments indicate that its applications can be made in ceramic and cement industry. It has proved its suitability for the manufacture of mineral wood.

Zircon: It is a source of zirconium metal and hafnium. Zircon powder is extensively employed as a moulding material for casting heavy cylinders, porcelain wares, etc.

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